Physics at the Tevatron

Lecture II

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Outline

- ## Lecture I
  - The Tevatron, CDF and DØ
  - Production Cross Section Measurements
    - Lepton identification
- ## Lecture II
  - The W boson mass, the Top Quark and the Higgs Boson
    - Lepton calibration, jet energy scale and b-tagging
- ## Lecture III
  - B_s mixing and $B_s \rightarrow \mu\mu$ rare decay
    - Vertex resolution and particle identification
- ## Lecture IV
  - Supersymmetry and High Mass Dilepton/Diphoton
    - Missing E_T

All lectures available at:
http://www−atlas.lbl.gov/~heinemann/homepage/publictalk.html

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- Top quark is the heaviest known fundamental particle
  - Today: m_{top}=170.9+-1.8 GeV
  - Run 1: m_{top}=178+-4.3 GeV/c^2
  - Is this large mass telling us something about electroweak symmetry breaking?
    - Top yukawa coupling:
    - $<H>/(\sqrt{2}\, m_{top})$ = 1.019+-0.011
- Masses related through radiative corrections:
  - $m_W \sim M_{top}^2$
  - $m_W \sim \ln(m_H)$
- If there are new particles the relation might change:
  - Precision measurement of top quark and W boson mass can reveal new physics
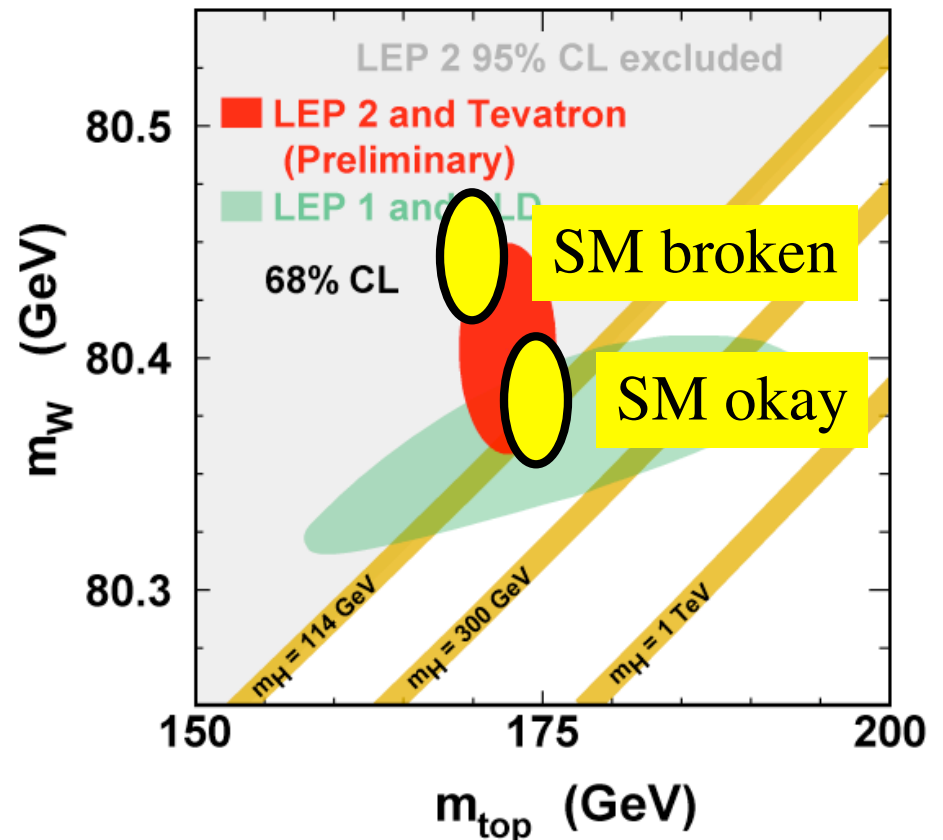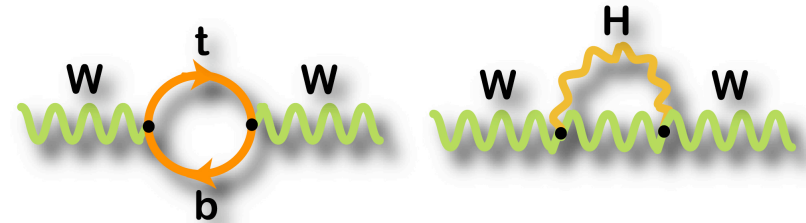
The W$^\pm$ boson

W Boson mass

- ## Real precision measurement:
  - LEP: $M_W = 80.367 \pm 0.033$ GeV/c^2
  - Precision: 0.04%
    - => Very challenging!

- ## Main measurement ingredients:
  - Lepton p_T
  - Hadronic recoil parallel to lepton: $u_{||}$

- ## Z→ll superb calibration sample:
  - but statistically limited:
    - About a factor 10 less Z's than W's
    - Most systematic uncertainties are related to size of Z sample
   - Will scale with $1/\sqrt{N_Z}$ (=$1/\sqrt{L}$)
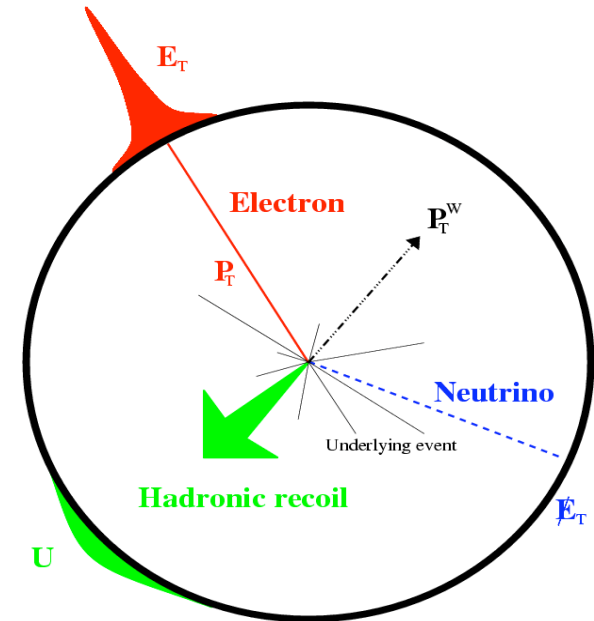
$$m_T = \sqrt{2 p_T^l \not{p}_T (1 - \cos \Delta\phi)},$$
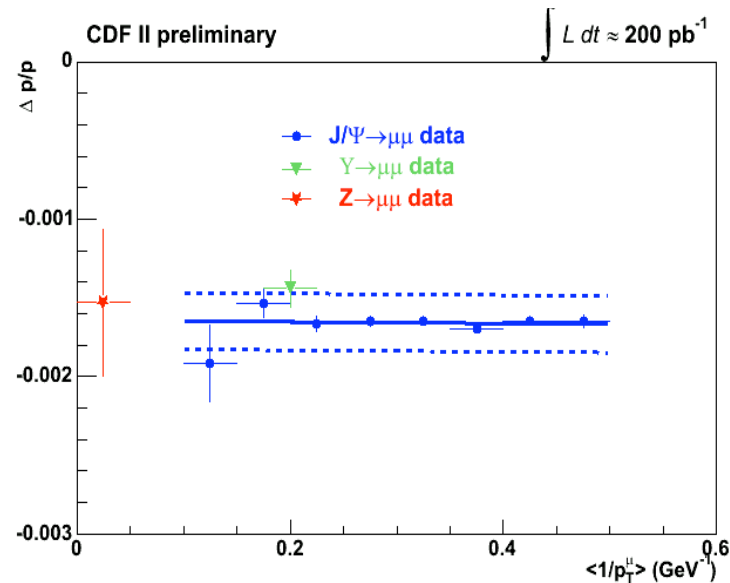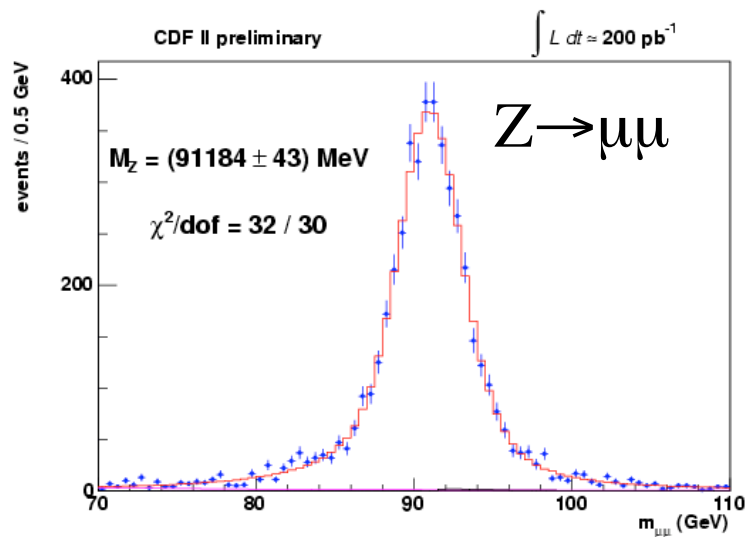
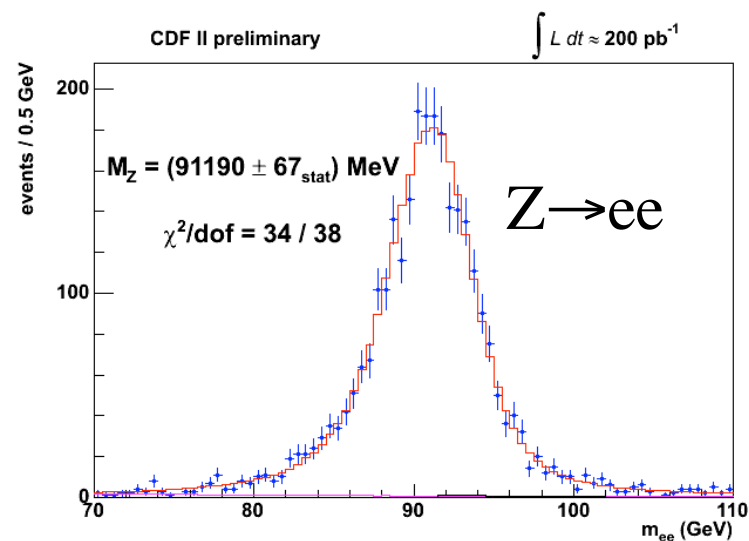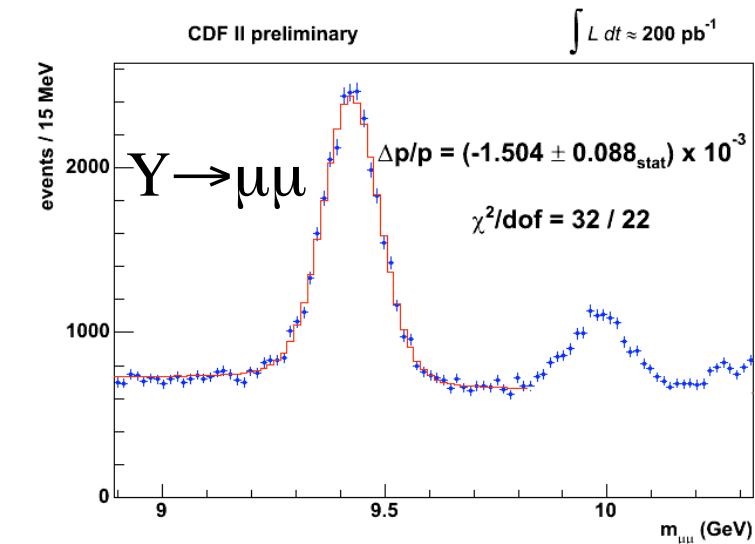$$\not{p}_T \approx |p_T + u_{||}|$$

$$m_T \approx 2 p_T \sqrt{1 + u_{||}/p_T} \approx 2 p_T + u_{||}$$

Lepton Momentum Scale

- Momentum scale:

  – Cosmic ray data used for detailed cell-by-cell calibration of CDF drift chamber

  – E/p of e+ and e- used to make further small corrections to p measurement

  – Peak position of overall E/p used to set electron energy scale

    - Tail sensitive to passive material

$\chi^2/dof = 17 / 16$

$E/p \; (W \rightarrow e\nu)$

COT cell and wire alignment

With track-level corrections

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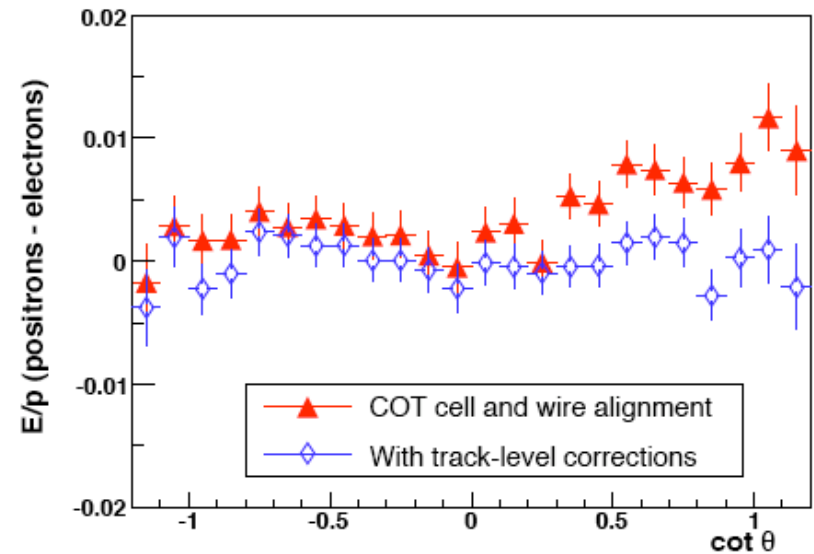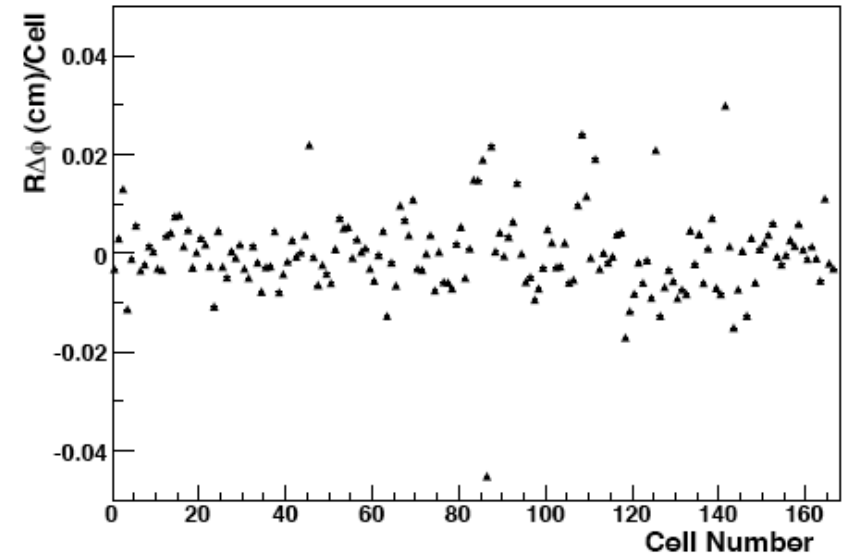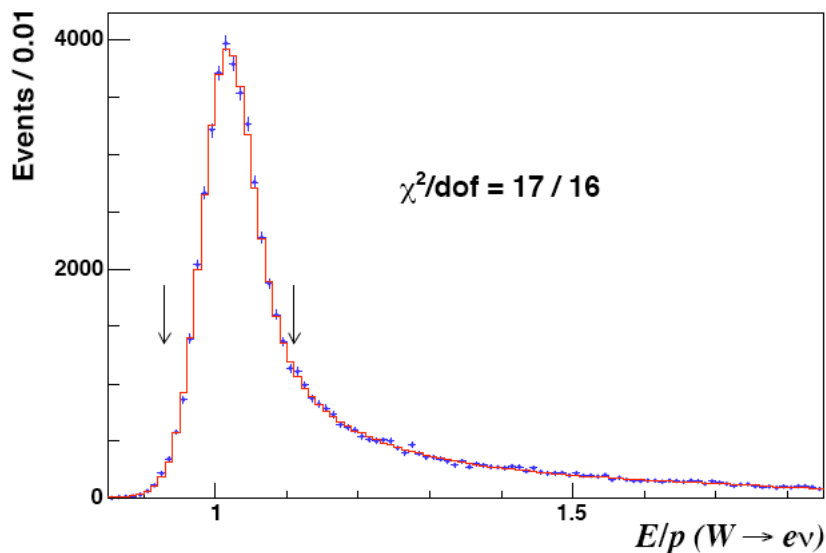
Lepton Momentum Scale and Resolution

- Systematic uncertainty on momentum scale: 0.04%

Systematic Uncertainties

m_T Fit Uncertainties			
Source	$W \to \mu\nu$	$W \to e\nu$	Correlation
Tracker Momentum Scale	17	17	100%
Calorimeter Energy Scale	0	25	0%
Lepton Resolution	3	9	0%
Lepton Efficiency	1	3	0%
Lepton Tower Removal	5	8	100%
Recoil Scale	9	9	100%
Recoil Resolution	7	7	100%
Backgrounds	9	8	0%
PDFs	11	11	100%
W Boson p_T	3	3	100%
Photon Radiation	12	11	100%
Statistical	54	48	0%
Total	60	62	-

Limited by data statistics

Limited by data and theoretical understanding

TABLE IX: Uncertainties in units of MeV on the transverse mass fit for m_W in the $W \to \mu\nu$ and $W \to e\nu$ samples.

- Overall uncertainty 60 MeV for both analyses
  - Careful treatment of correlations between them
- Dominated by stat. error (50 MeV) vs syst. (33 MeV)
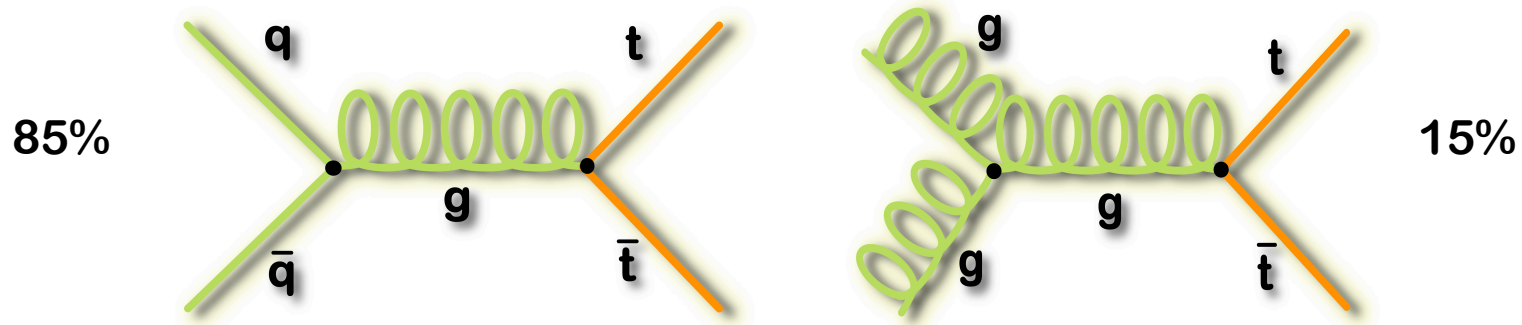
W Boson Mass
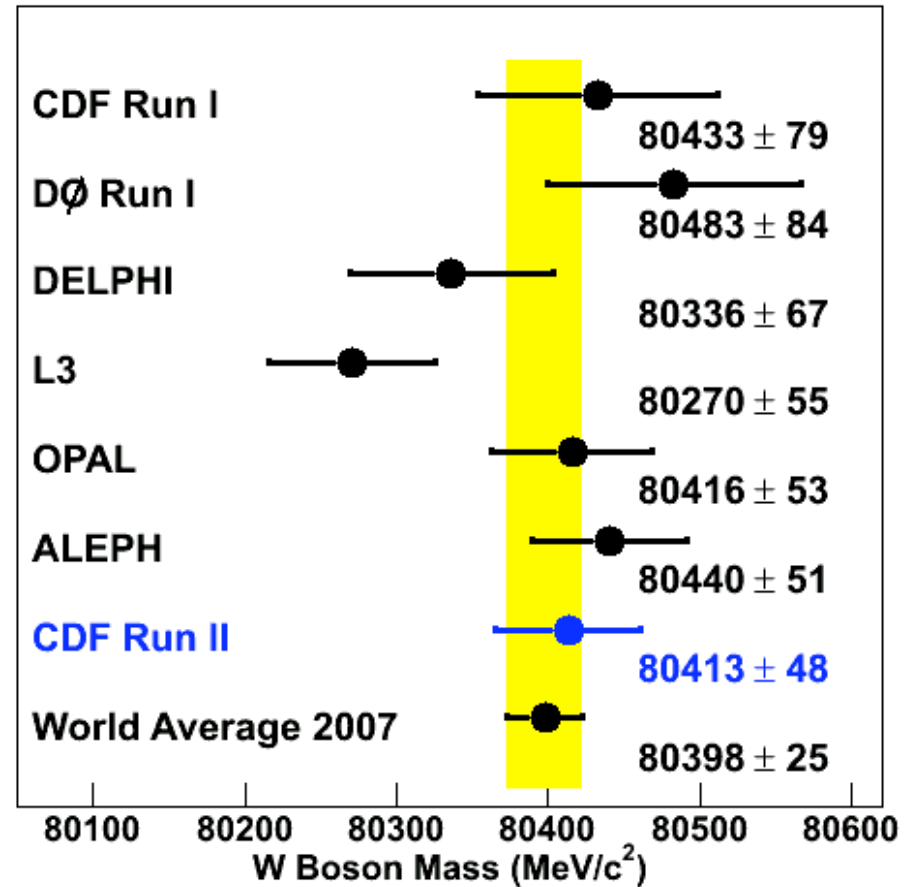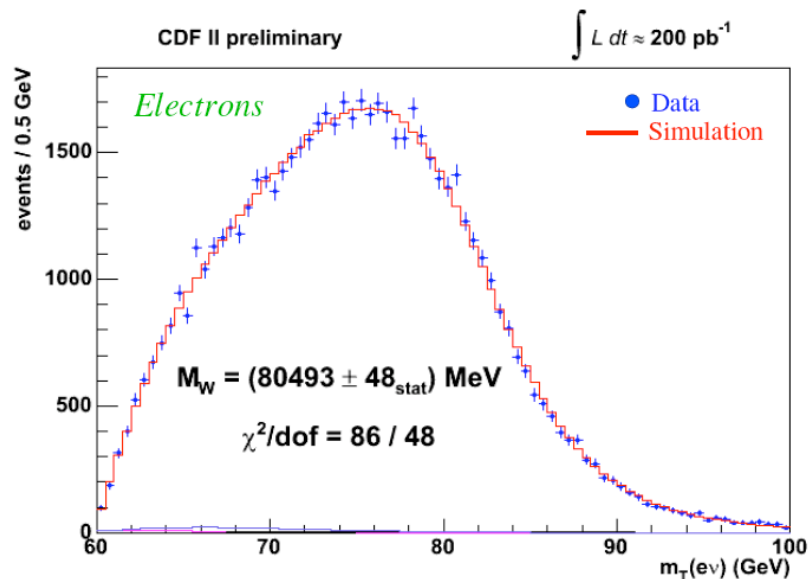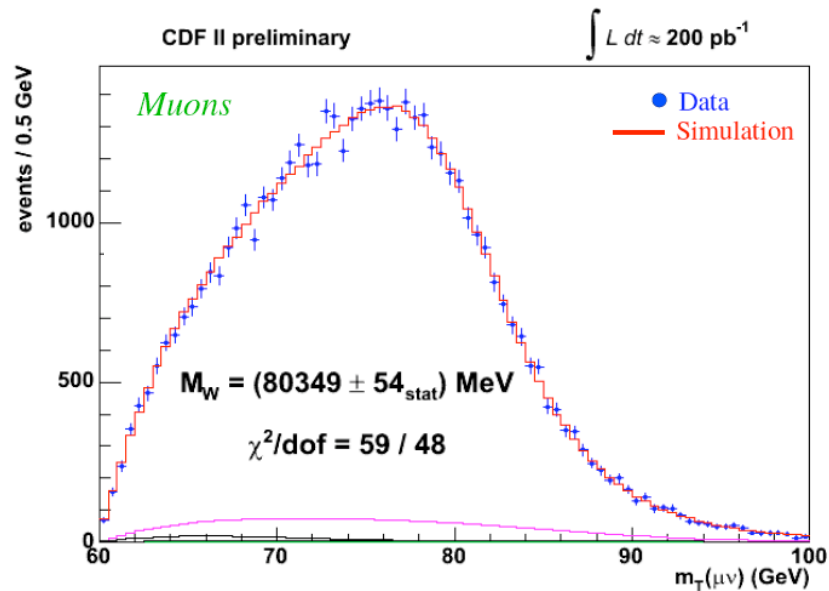
- New world average:

  $M_w = 80398 \pm 25$ MeV

- Ultimate Run 2 precision:

  ~15 MeV

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The Top Quark

Top Quark Production and Decay

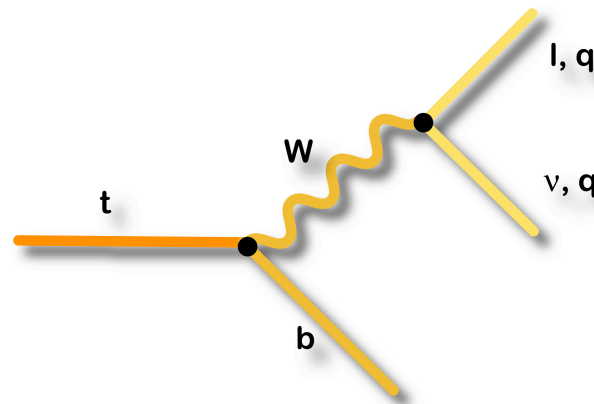- At Tevatron, mainly produced in pairs via the strong interaction

85%

15%

Br(t →Wb) ~ 100%

- Decay via the electroweak interactions
  Final state is characterized by the decay of the W boson

Dilepton

Lepton+Jets

All-Jets

Different sensitivity and challenges in each channel
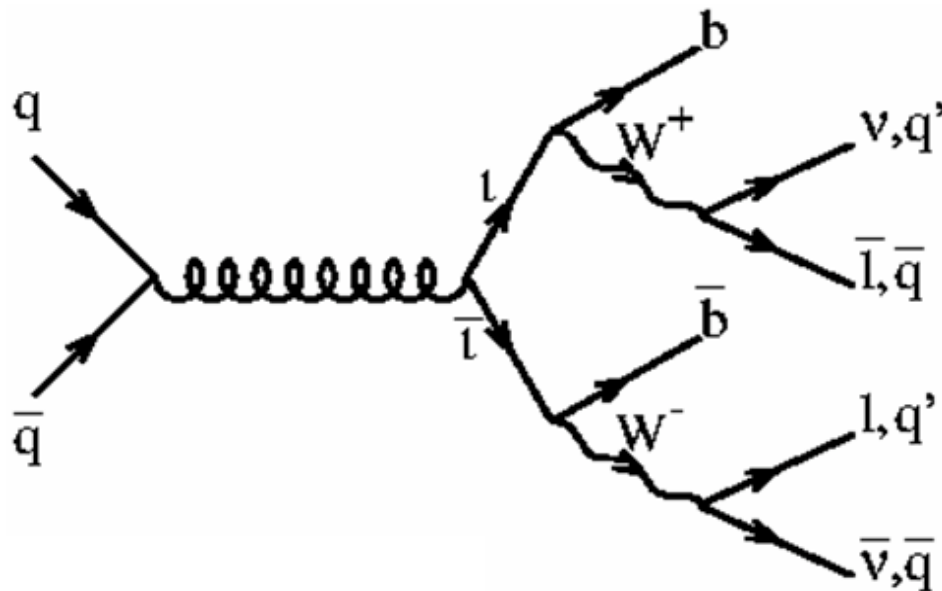
How to identify the top quark

SM: $\bar{t}t$ pair production, Br($t \to bW$)=100% , Br($W \to l\nu$)=1/9=11%

dilepton   (4/81)   2 leptons + 2 jets + missing E_T
l+jets   (24/81)   1 lepton + 4 jets + missing E_T
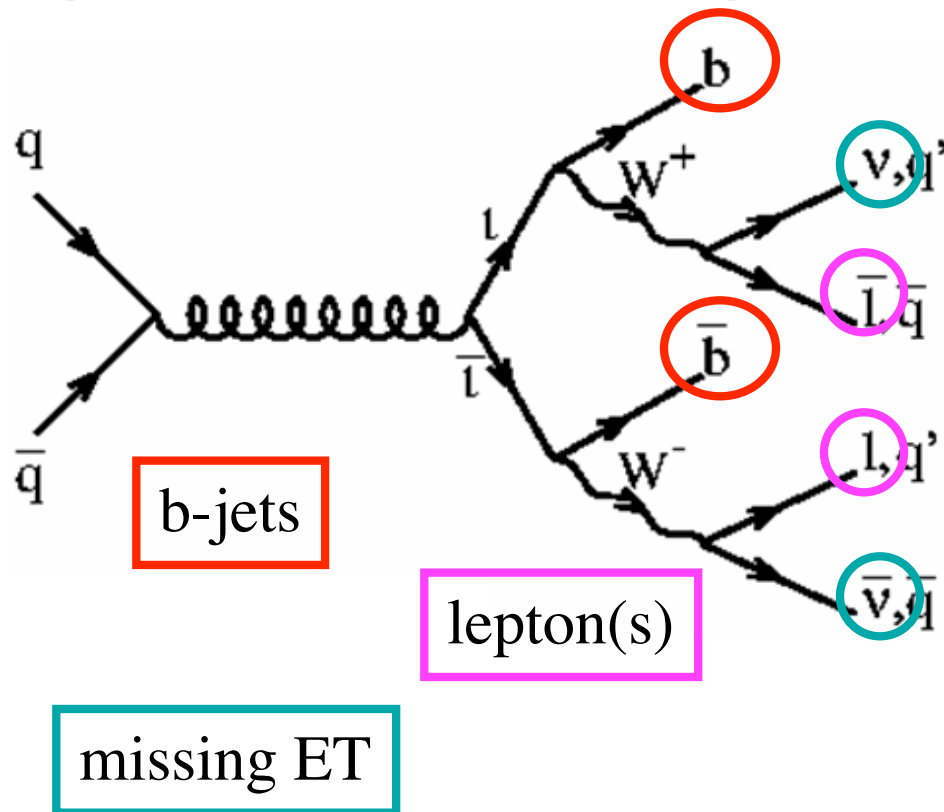fully hadronic (36/81)   6 jets

(here: $l=e,\mu$)

How to identify the top quark

SM: $\bar{t}t$ pair production, Br($t \rightarrow bW$)=100% , Br(W->$l\nu$)=1/9=11%

dilepton *(4/81)* **2 leptons + 2 jets + missing E_T**
lepton+jets *(24/81)* 1 lepton + 4 jets + missing E_T
fully hadronic *(36/81)* 6 jets

b-jets

lepton(s)

missing ET

How to identify the top quark

SM: $t\bar{t}$ pair production, $Br(t \rightarrow bW)=100\%$, $Br(W \rightarrow l\nu)=1/9=11\%$

dilepton   (4/81)   2 leptons + 2 jets + missing E_T
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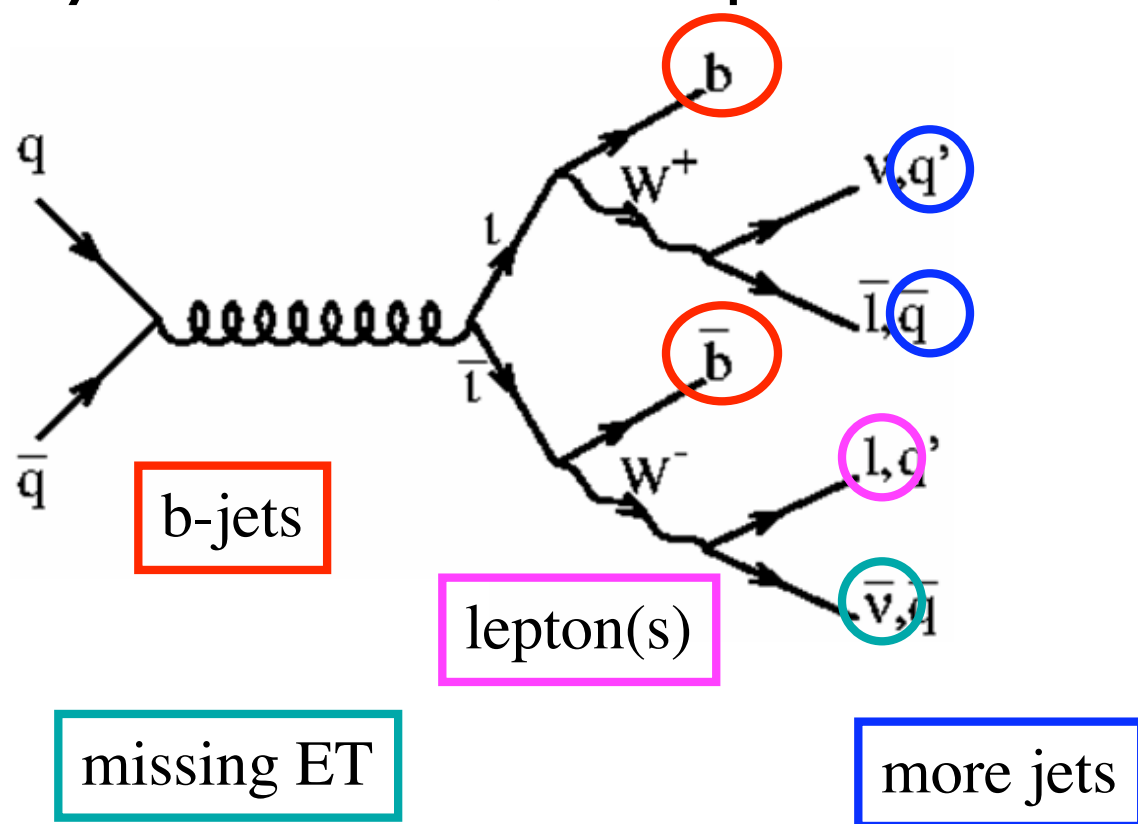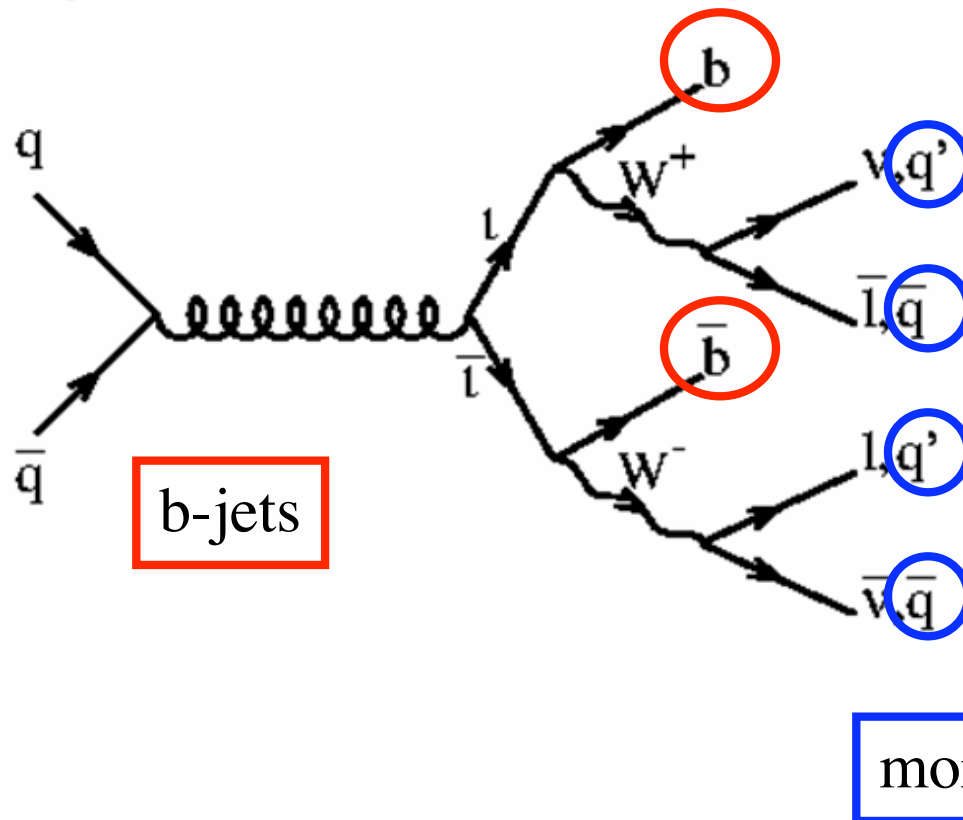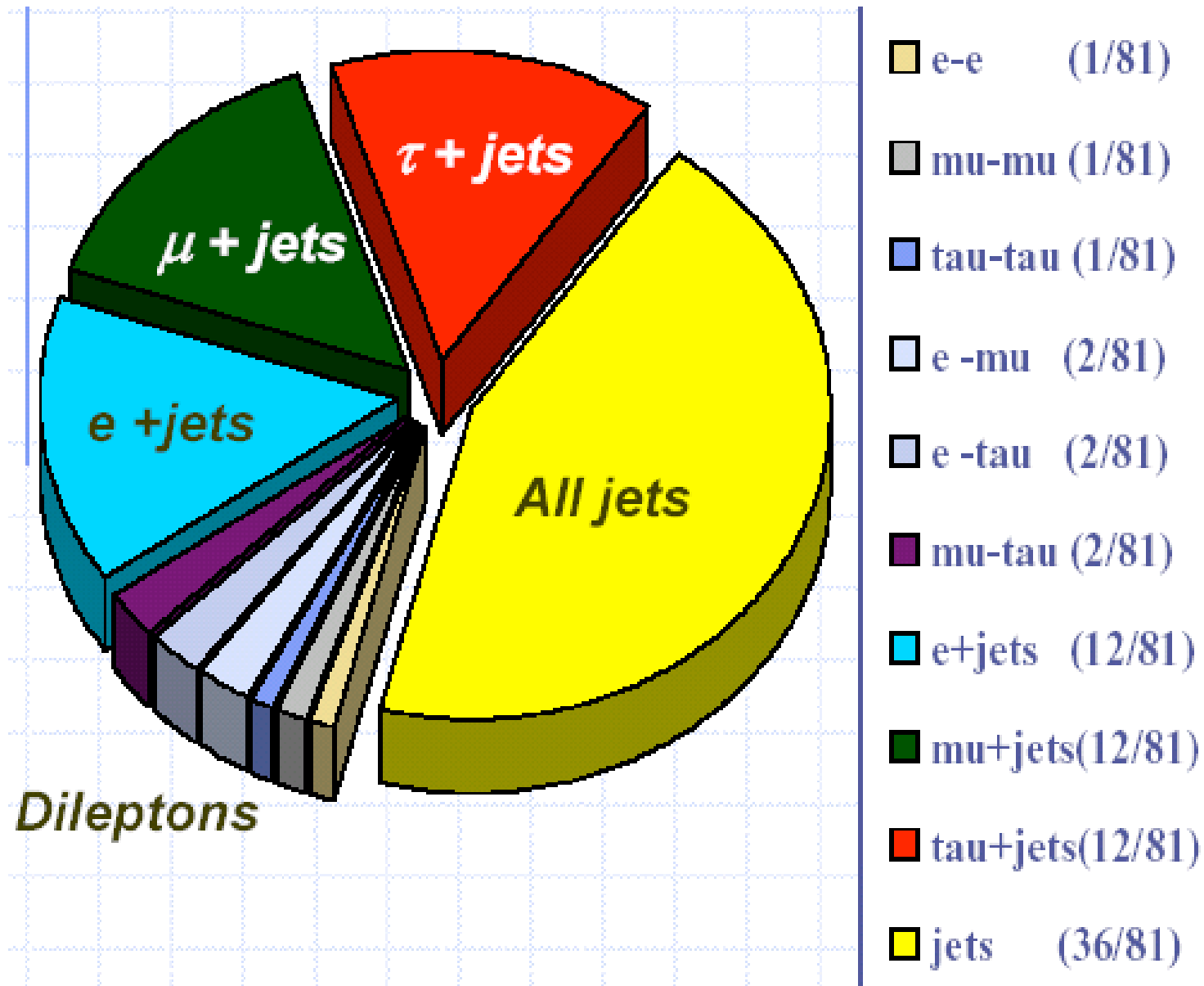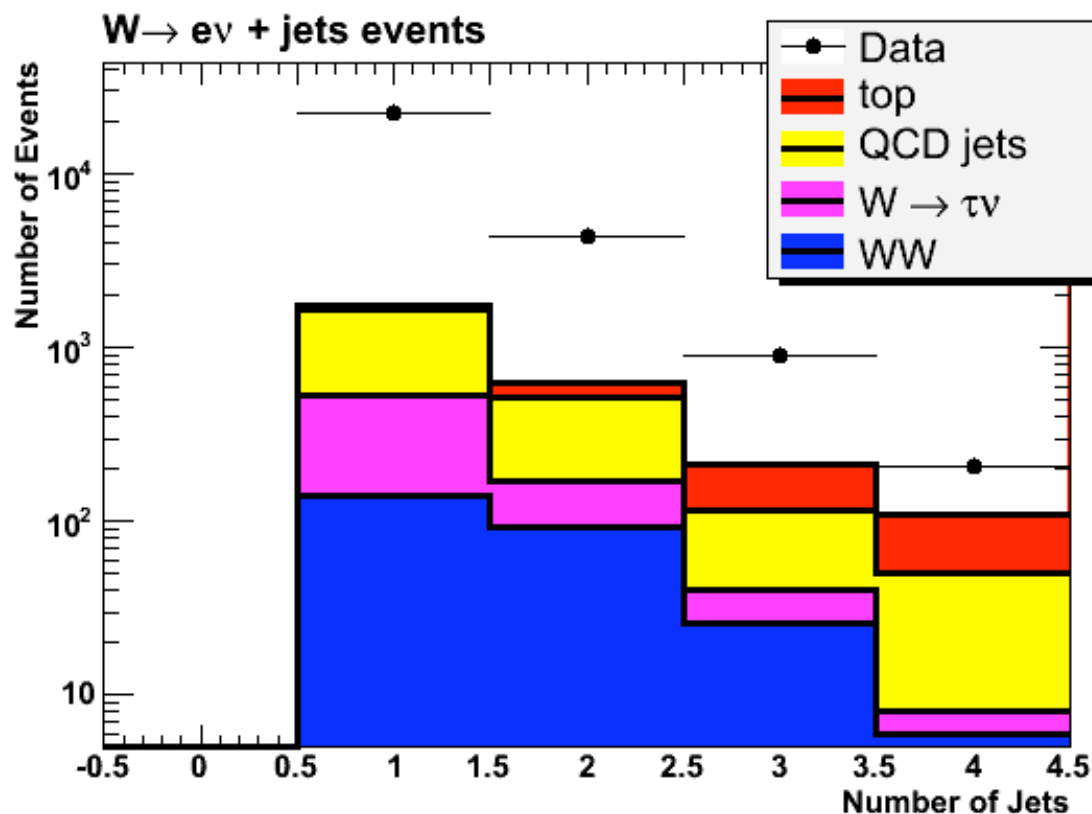fully hadronic (36/81)   6 jets

SM: $t\bar{t}$ pair production, Br(t→bW)=100% , Br(W->lv)=1/9=11%

dilepton	(4/81)	2 leptons + 2 jets + missing E_T
lepton+jets	(24/81)	1 lepton + 4 jets + missing E_T
fully hadronic	(36/81)	6 jets

b-jets

more jets

Top Event Categories

τ + jets

μ + jets

e +jets

All jets

Dileptons

- e-e (1/81)
- mu-mu (1/81)
- tau-tau (1/81)
- e -mu (2/81)
- e -tau (2/81)
- mu-tau (2/81)
- e+jets (12/81)
- mu+jets(12/81)
- tau+jets(12/81)
- jets (36/81)

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Finding the Top

- **Top is overwhelmed by backgrounds:**
  - Even for 4 jets the top fraction is only 30%
    - This is very different to the LHC (about 80%)!

- **Use b-jets to purify sample**
 - Also analyses using Neural Network to separate top kinematically

Finding the b-jets

- ## Exploit large lifetime of the b-hadron
  - ### B-hadron flies before it decays: $d = c\tau$
    - Lifetime $\tau = 1.5$ ps^{-1}
    - $d = c\tau = 460$ μm
    - Can be resolved with silicon detector resolution

- ## Procedure "Secondary Vertex":
  - ### reconstruct primary vertex:
    - resolution ~ 30 μm
  - ### Search tracks inconsistent with primary vertex (large d_0):
    - Candidates for secondary vertex
    - See whether three or two of those intersect at one point
  - ### Require displacement of secondary from primary vertex
    - Form L_{xy}: transverse decay distance projected onto jet axis:
      - $L_{xy} > 0$: b-tag along the jet direction => real b-tag or mistag
      - $L_{xy} < 0$: b-tag opposite to jet direction => mistag!
    - Significance: $\delta L_{xy} / L_{xy} > 7$ i.e. 7σ significant displacement
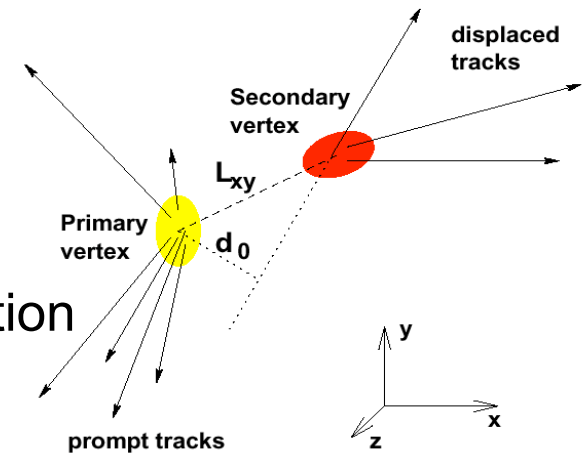
Characterise the B-tagger: Efficiency

- ## Efficiency of tagging a true b-jet
  - Use Data sample enriched in b-jets
  - Select jets with electron or muons
    - From semi-leptonic b-decay
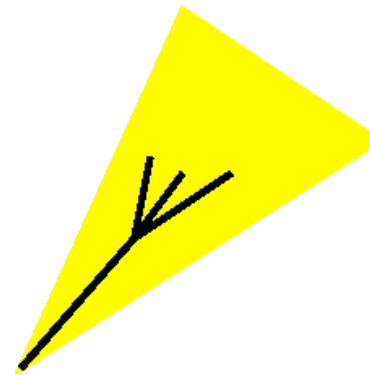 - Measure efficiency in data and MC
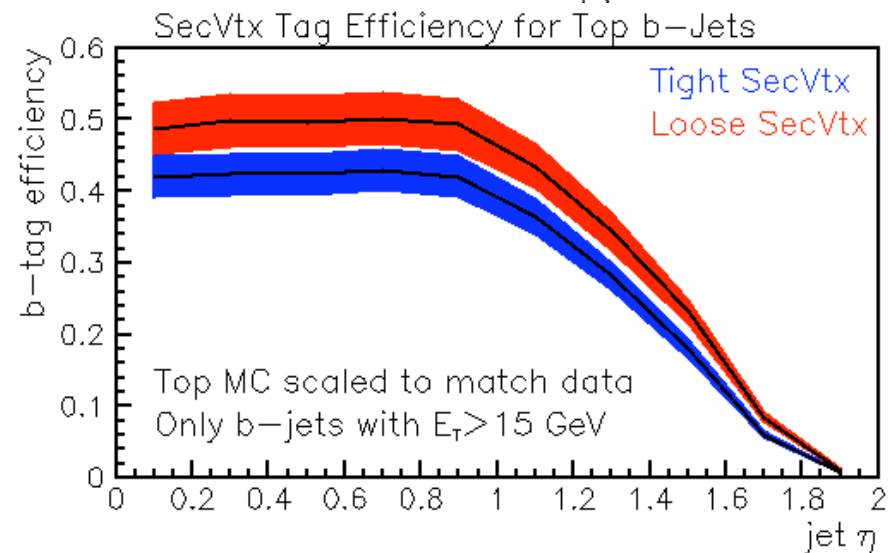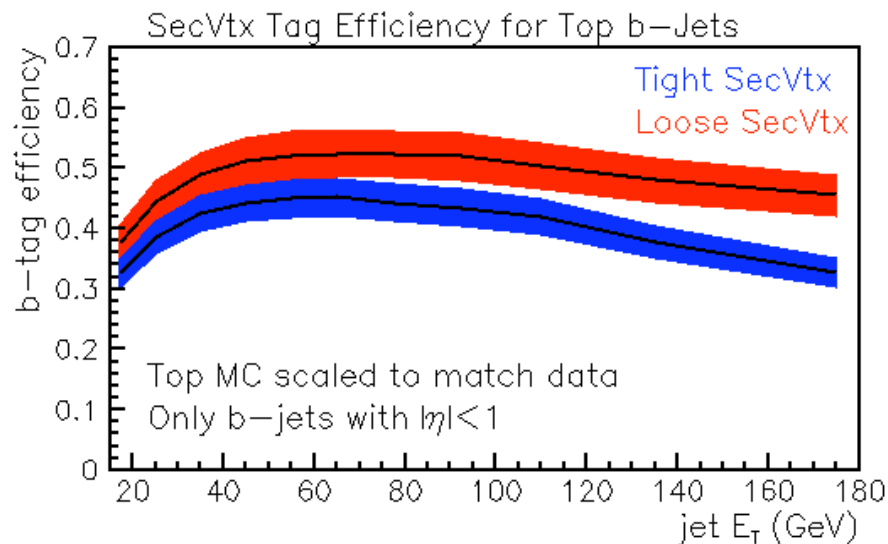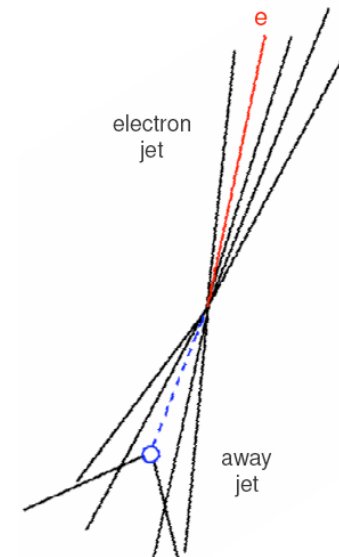
Achieve about 40-50%
(fall-off at high eta due to limited tracking coverage)

Characterise the B-tagger: Mistag rate

- ## Mistag Rate measurement:

  - Probability of light quarks to be misidentified

  - Use "negative" tags: $L_{xy}<0$

    - Can only arise due to misreconstruction

  - Mistag rate for E_T=50 GeV:

    - Tight: 0.5% (ε=43%)
    - Loose: 2% (ε=50%)

  - Depending on physics analyses:

    - Choose "tight" or "loose" tagging algorithm

"positive" tag   "negative" tag

SecVtx Mistag Rates

Tight SecVtx
Loose SecVtx
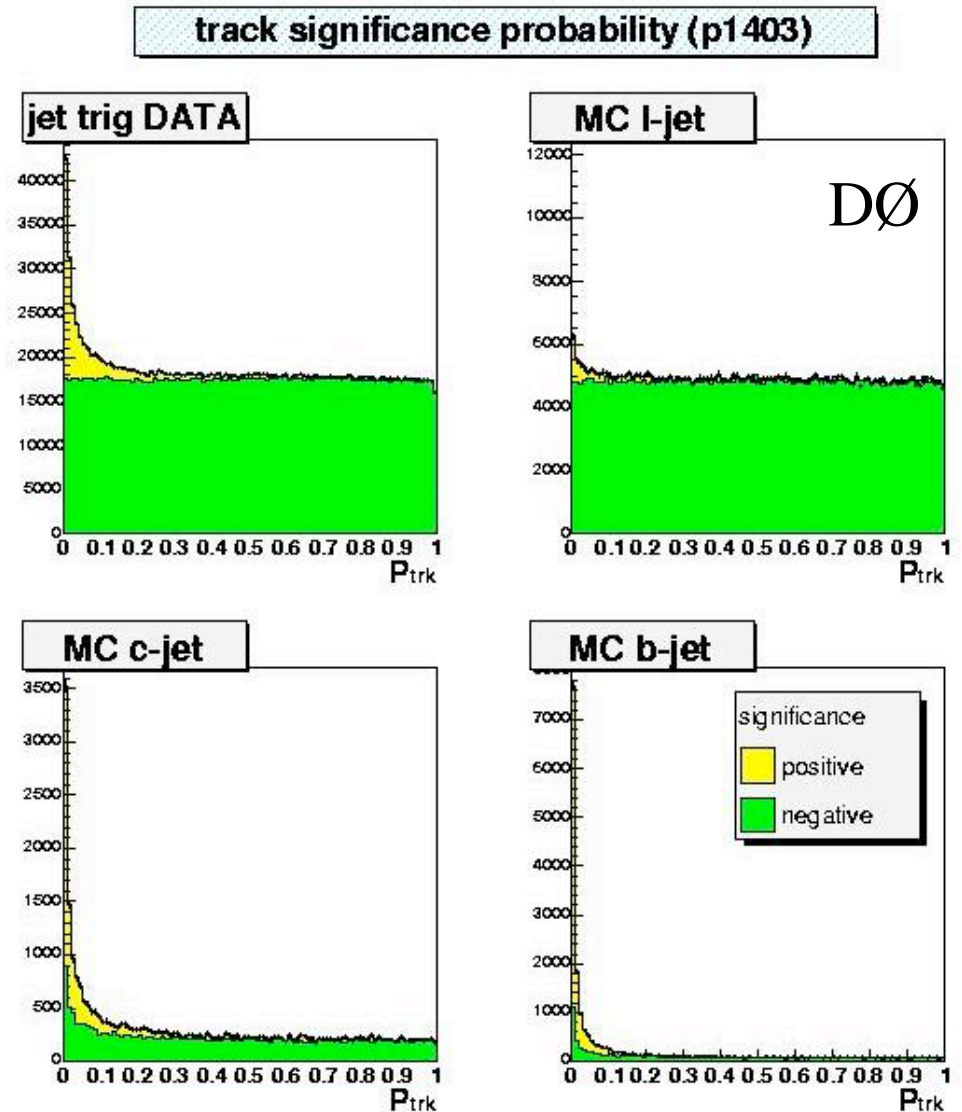
Only jets with $|\eta|<1$

mistag rate

jet E_T (GeV)
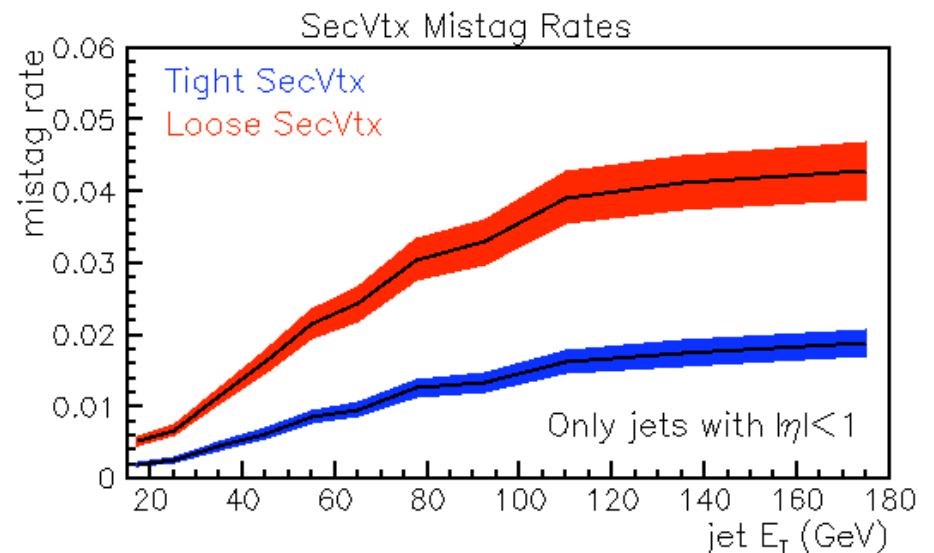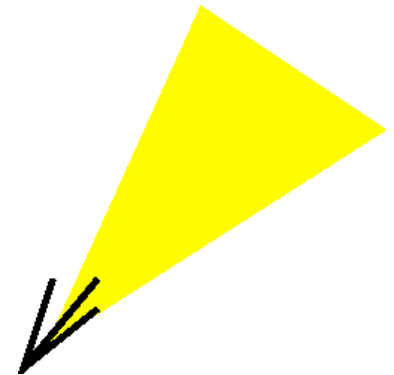
Jet Probability

- **Complementary to full secondary vertex reconstruction:**
  - Evaluate probability of tracks to be prompt
    - Multiply probabilities of individual tracks together
  - "Jet Probability"

- **Continuous distribution**
  - Can optimize cut valued for each analysis
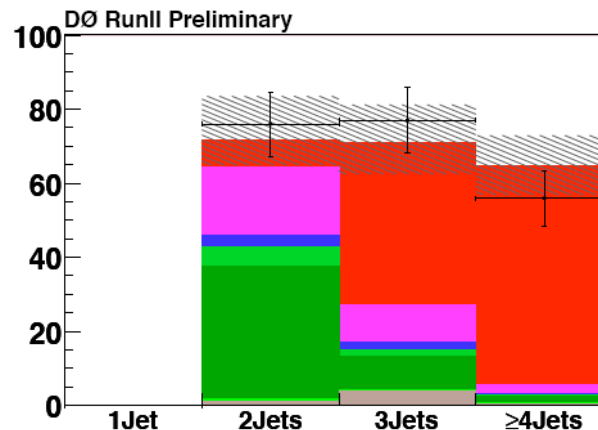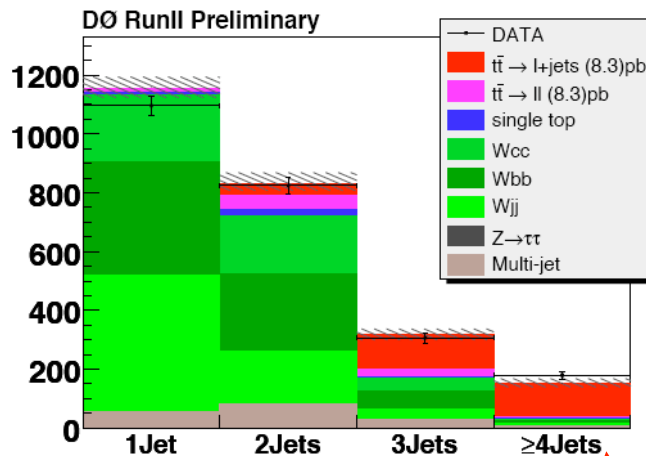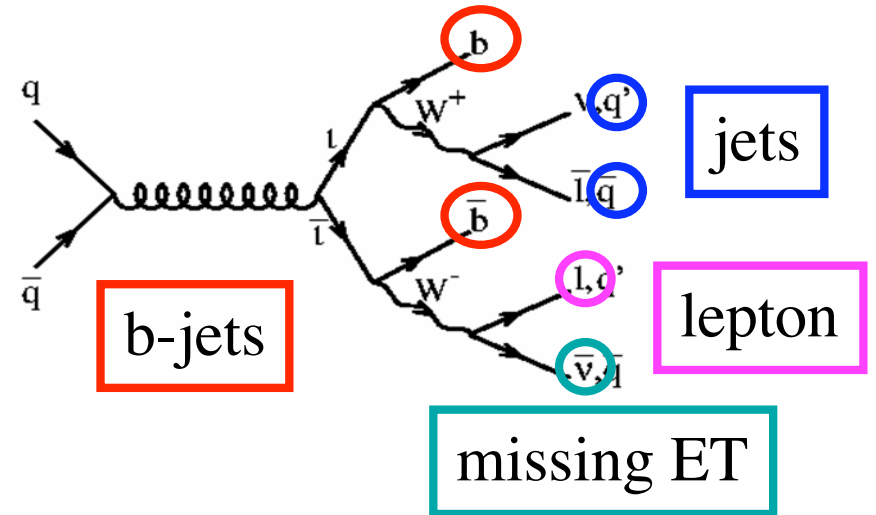 - Can also use this well for charm

Neural Net B-tagging

- ## Rather new for CDF and D0!
  - Nice to have continuous variable
  - Can be optimised depending on analysis requirements

- ## Several strategies
  - DØ uses 7 input variables from their three standard taggers
    - increase efficiency by 30% or purity by 30% over any single one
  - CDF uses 24 variables on top of SecVtx only
    - Improve purity of tags by 50-70%
    - Sacrifice 10% of efficiency

CDF II Preliminary

DØ Preliminary
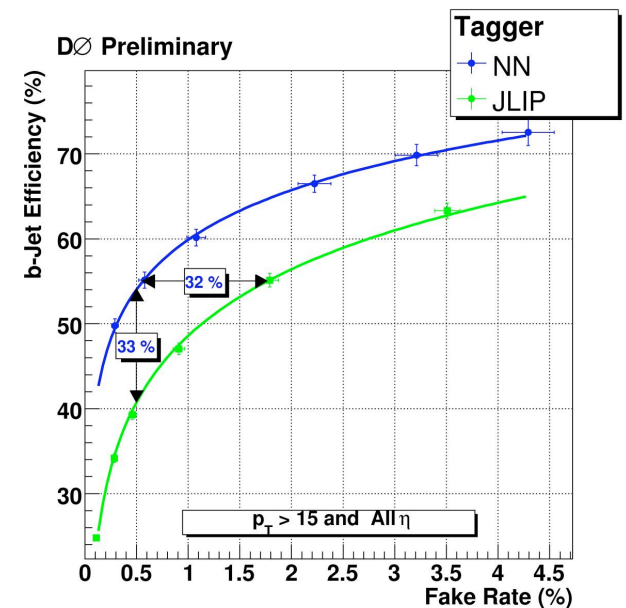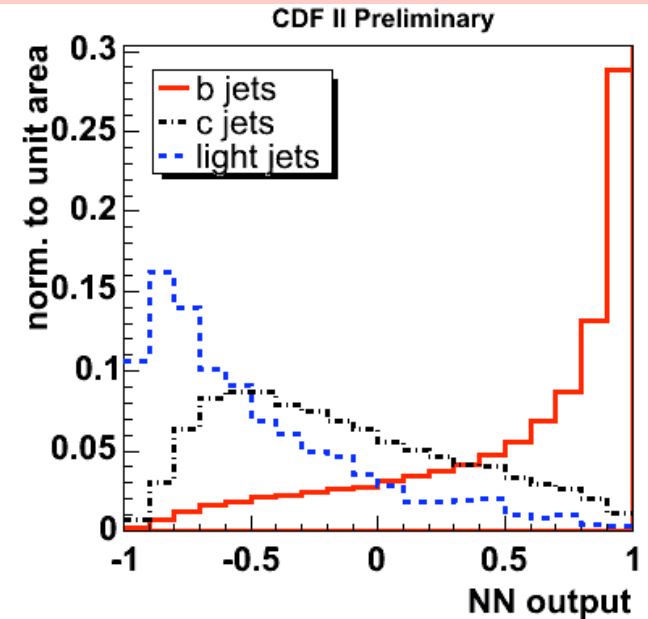
The Top Signal: Lepton + Jets

- ## Select:
  - 1 electron or muon
  - Large missing E_T
  - 1 or 2 b-tagged jets

jets

b-jets

lepton

missing ET

DØ RunII Preliminary

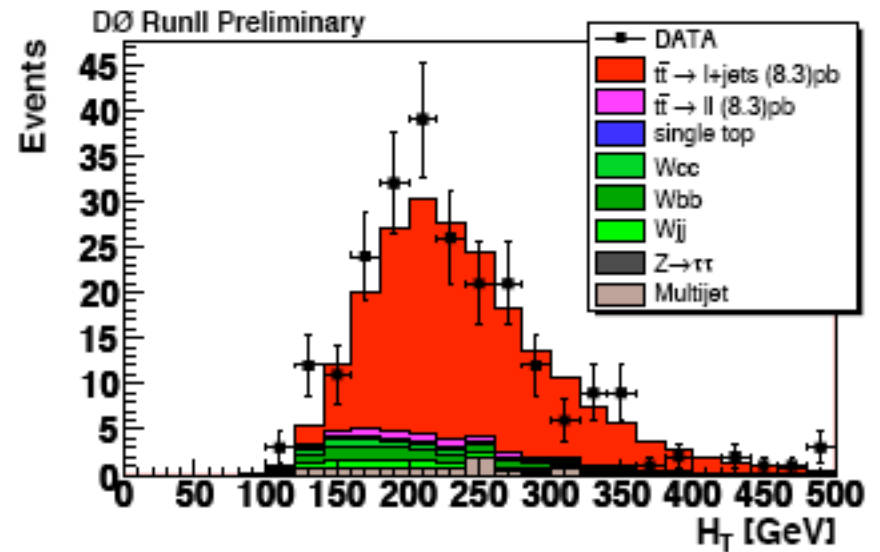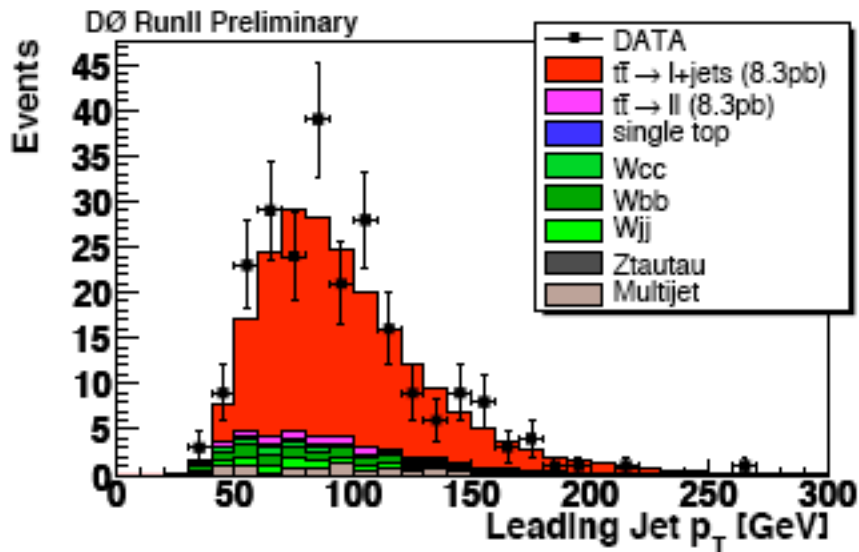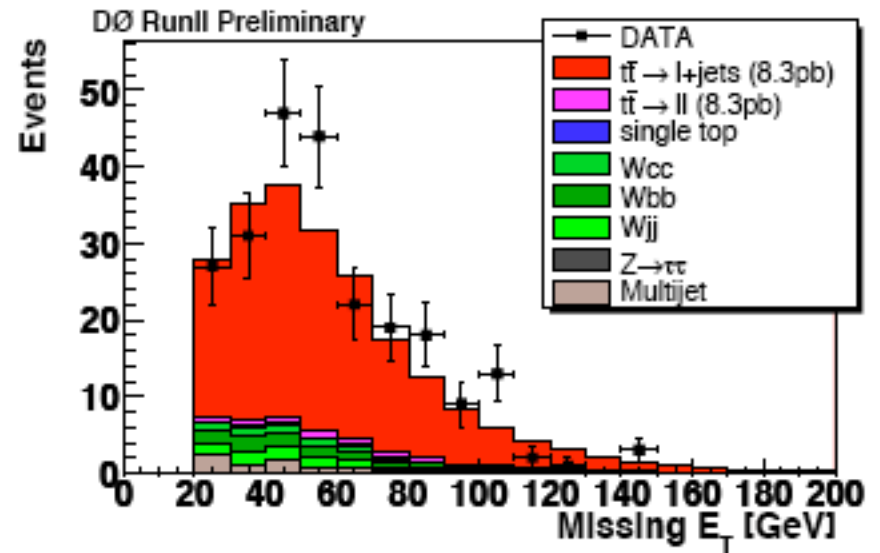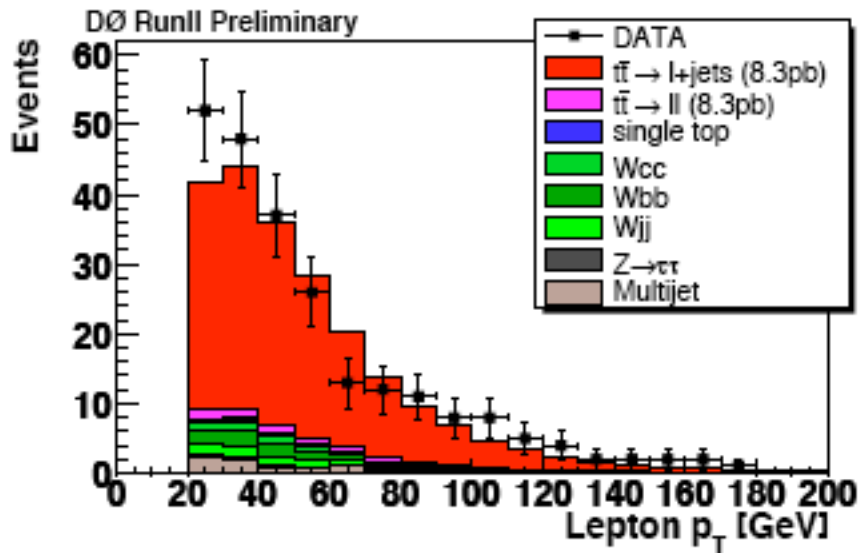|	
DATA	
$t\bar{t} \to l+jets$ (8.3)pb	
$t\bar{t} \to ll$ (8.3)pb	
single top	
Wcc	
Wbb	
Wjj	
$Z \to \tau\tau$	
Multi-jet	

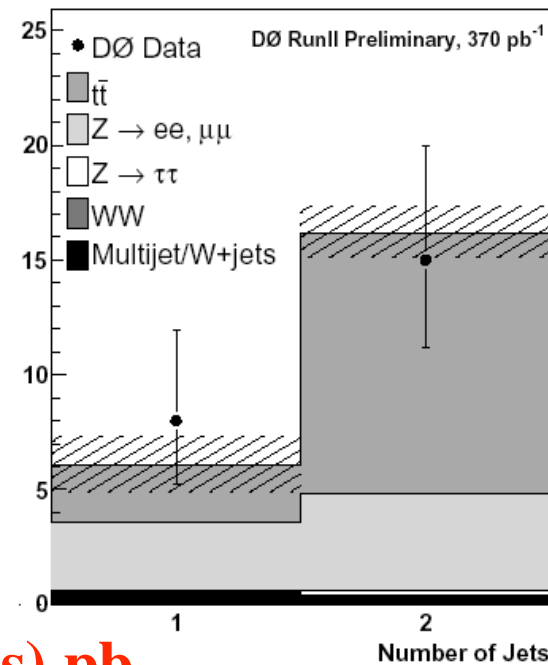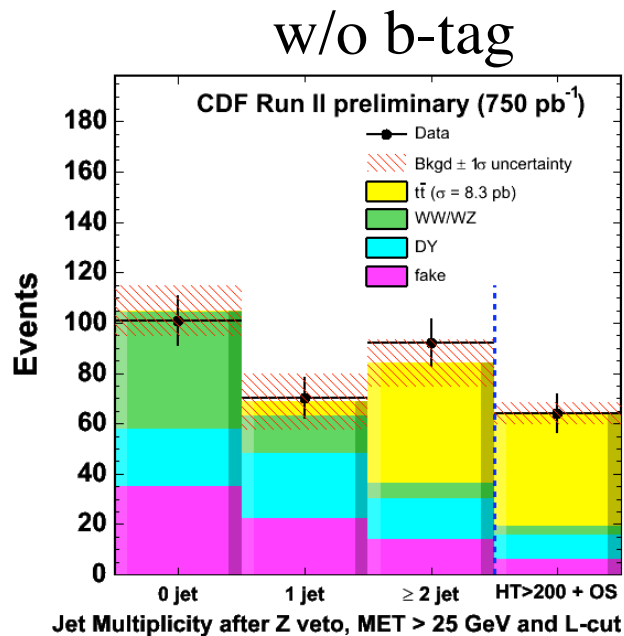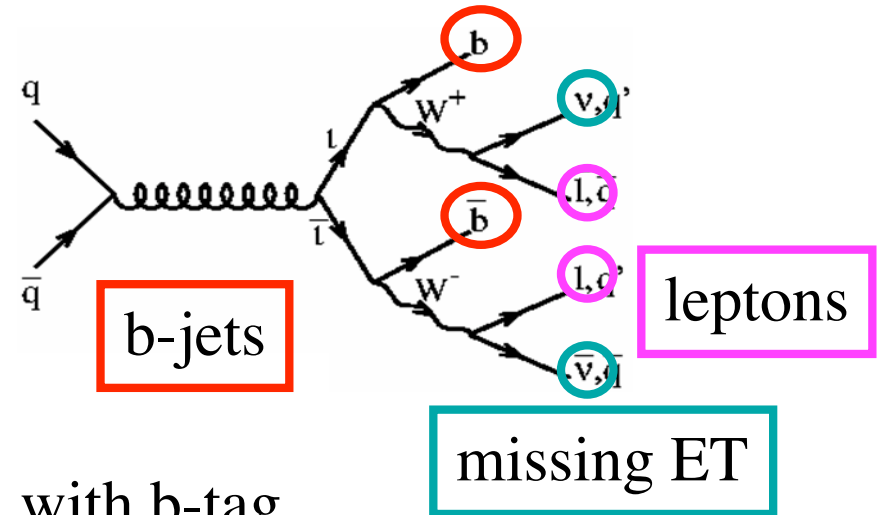66 double-tagged events, nearly no background

Check backgrounds

Top Signal

$\sigma(t\bar{t}) = 8.3^{+0.6}_{-0.5}(\text{stat}) \pm 1.1 \text{ (syst) pb}$

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Data and Monte Carlo Comparison

The Top Signal: Dilepton

- **Select:**
  - 2 leptons: ee, eμ, μμ
  - Large missing E_T
  - 2 jets (with or w/o b-tag)

b-jets

leptons

missing ET

w/o b-tag

CDF Run II preliminary (750 pb^{-1})

- Data
- Bkgd ± 1σ uncertainty
- $t\bar{t}$ (σ = 8.3 pb)
- WW/WZ
- DY
- fake

Events

0 jet   1 jet   ≥ 2 jet   HT>200 + OS

Jet Multiplicity after Z veto, MET > 25 GeV and L-cut

with b-tag

- DØ Data
- $t\bar{t}$
- Z → ee, μμ
- Z → ττ
- WW
- Multijet/W+jets

DØ RunII Preliminary, 370 pb^{-1}

Number of Jets

**σ=6.2 ± 0.9 (stat) ± 0.9 (sys) pb**

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The Top Cross Section
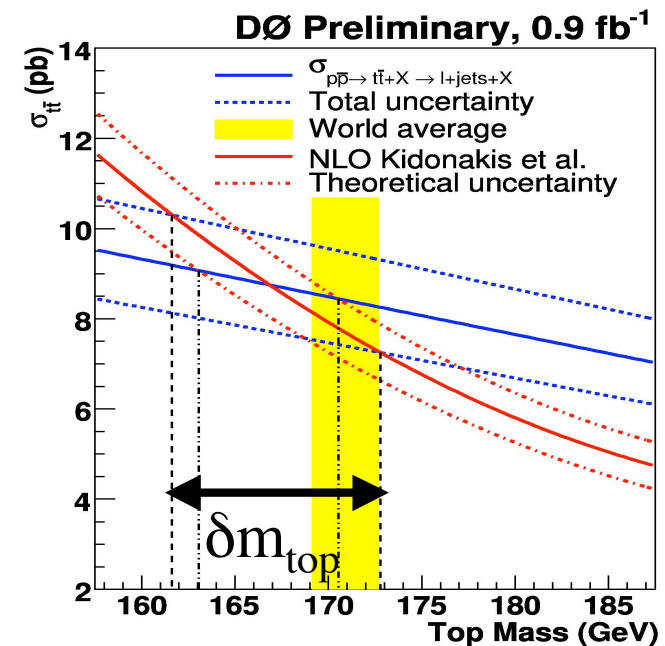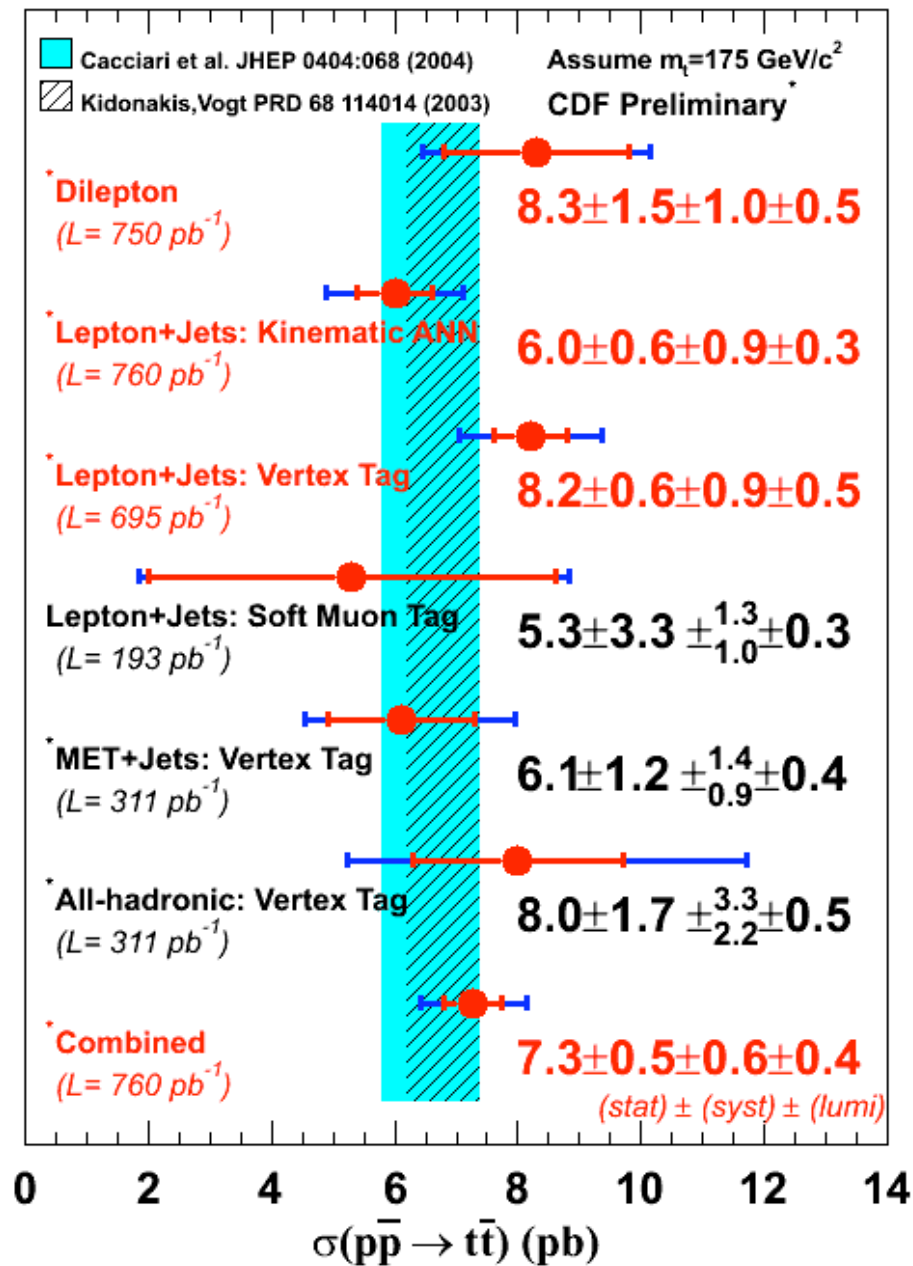
- **Measured using many different techniques**
- **Good agreement**
  - between all measurements
  - between data and theory
- **Can be used to extract top mass:**
 - $m_{top} = 166.9\ ^{+7.0}_{-6.4}$ GeV/c^2

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Top Mass Measurement: tt→(blν)(bqq)

- 4 jets, 1 lepton and missing E_T
  - Which jet belongs to what?
  - Combinatorics!

- B-tagging helps:
  - 2 b-tags =>2 combinations
  - 1 b-tag   => 6 combinations
  - 0 b-tags =>12 combinations

- Two Strategies:
  - Template method:
    - Uses "best" combination
    - Chi2 fit requires m(t)=m($\bar{t}$)
  - Matrix Element method:
    - Uses all combinations
    - Assign probability depending on kinematic consistency with top
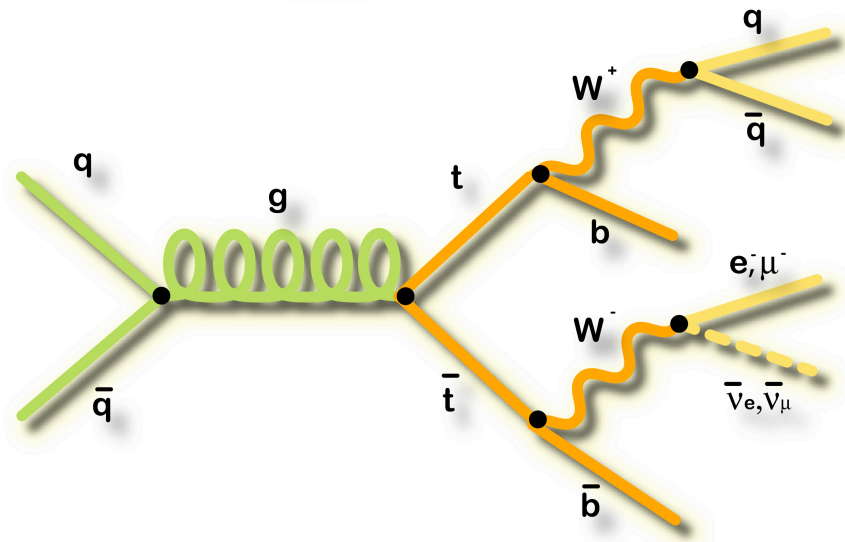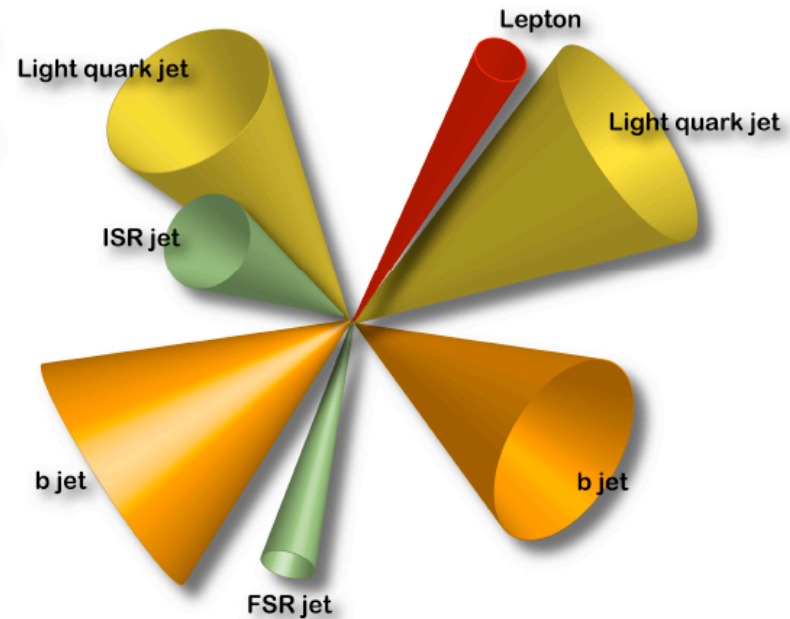
Top Mass Determination

- ## Inputs:
  - Jet 4-vectors
  - Lepton 4-vector
  - Remaining transverse energy, $p_{T,UE}$:
    - $p_{T,\nu} = -(p_{T,l} + p_{T,UE} + \sum p_{T,jet})$

- ## Constraints:
  - $M(l\nu) = M_W$
  - $M(q\bar{q}) = M_W$
  - $M(t) = M(\bar{t})$

- ## Unknown:
  - Neutrino p_z

- ## 1 unknown, 3 constraints:
  - Overconstrained
  - Can measure M(t) for each event: m_t^{reco}
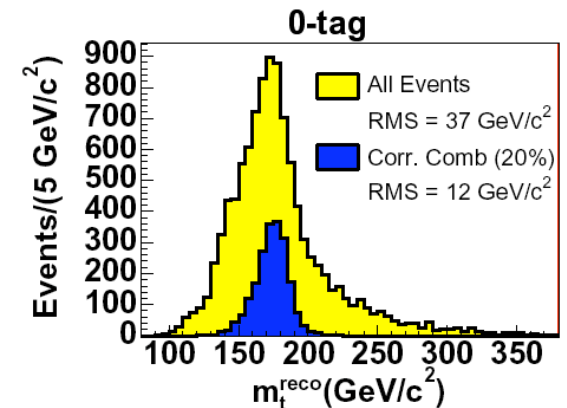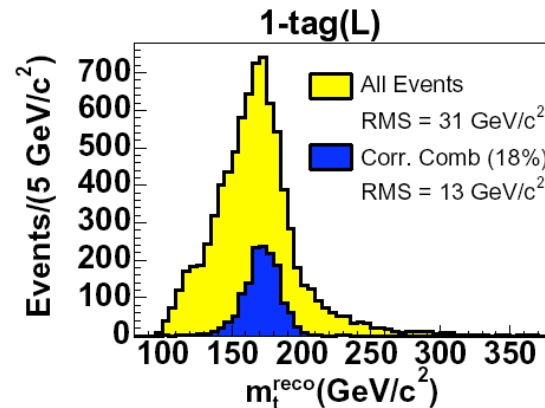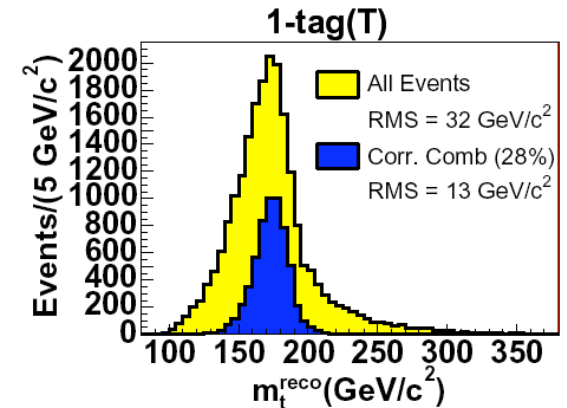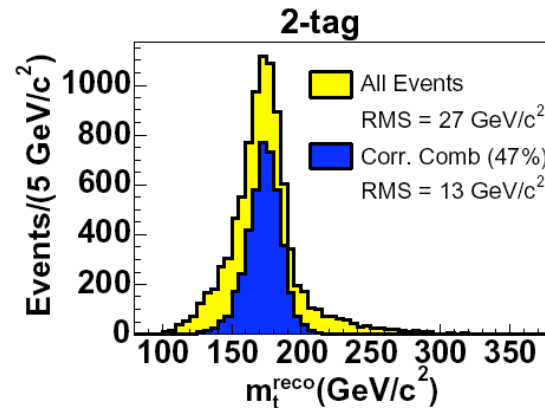
Selecting correct combination 20-50% of the time

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Jet Energy Scale

- **Jet energy scale**
  - Determine the energy of the partons produced in the hard scattering process
  - Instrumental effects:
    - Non-linearity of calorimeter
    - Response to hadrons
    - Poorly instrumented regions
  - Physics effects:
    - Initial and final state radiation
    - Underlying event
    - Hadronization
   - Flavor of parton

- **Test each in data and MC**
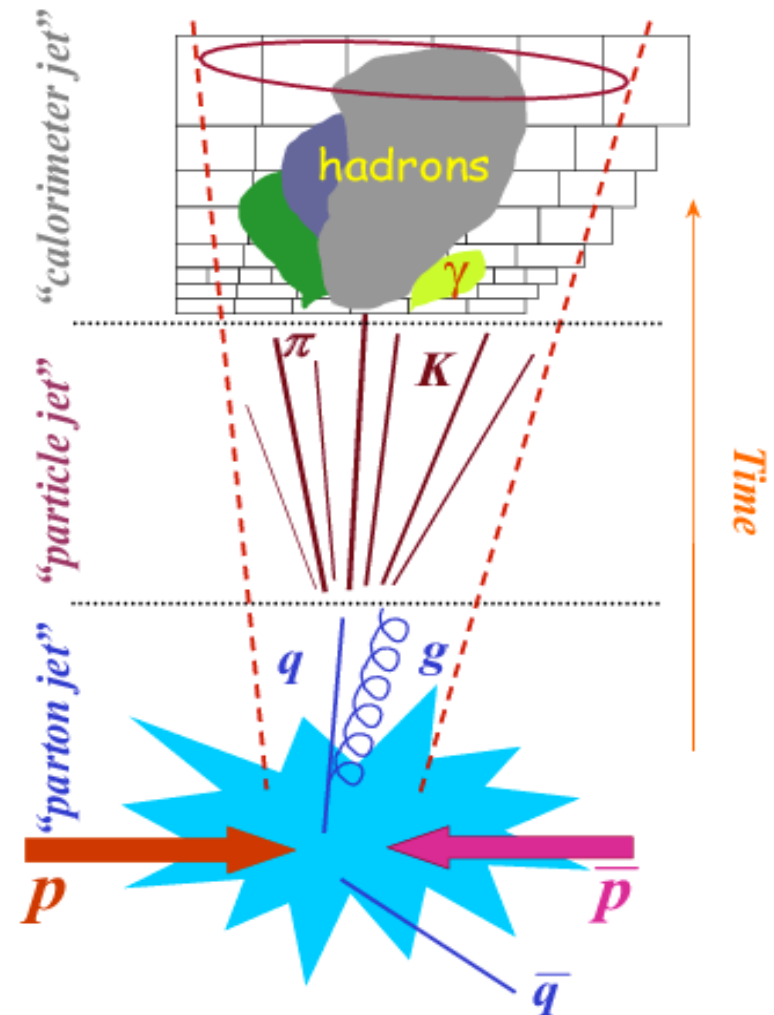
$$P_{T,jet}^{particle} = \left[P_{T,jet}^{measured} \times f_{rel} - MI \right] \times f_{abs}, \qquad P_T^{parton} = P_{T,jet}^{particle} - UE + OOC$$

Jet Energy Scale Studies

- **Measure energy response to charged particles**
  - Test beam and in situ
  - CDF: Response rather non-linear
  - DØ: compensating =>has better response
    - Some compensation "lost" due to shorter gate in run 2

- **CDF uses fast parameterized showers:**
 - GFLASH
  - Tuned to data

- **DØ uses full GEANT**
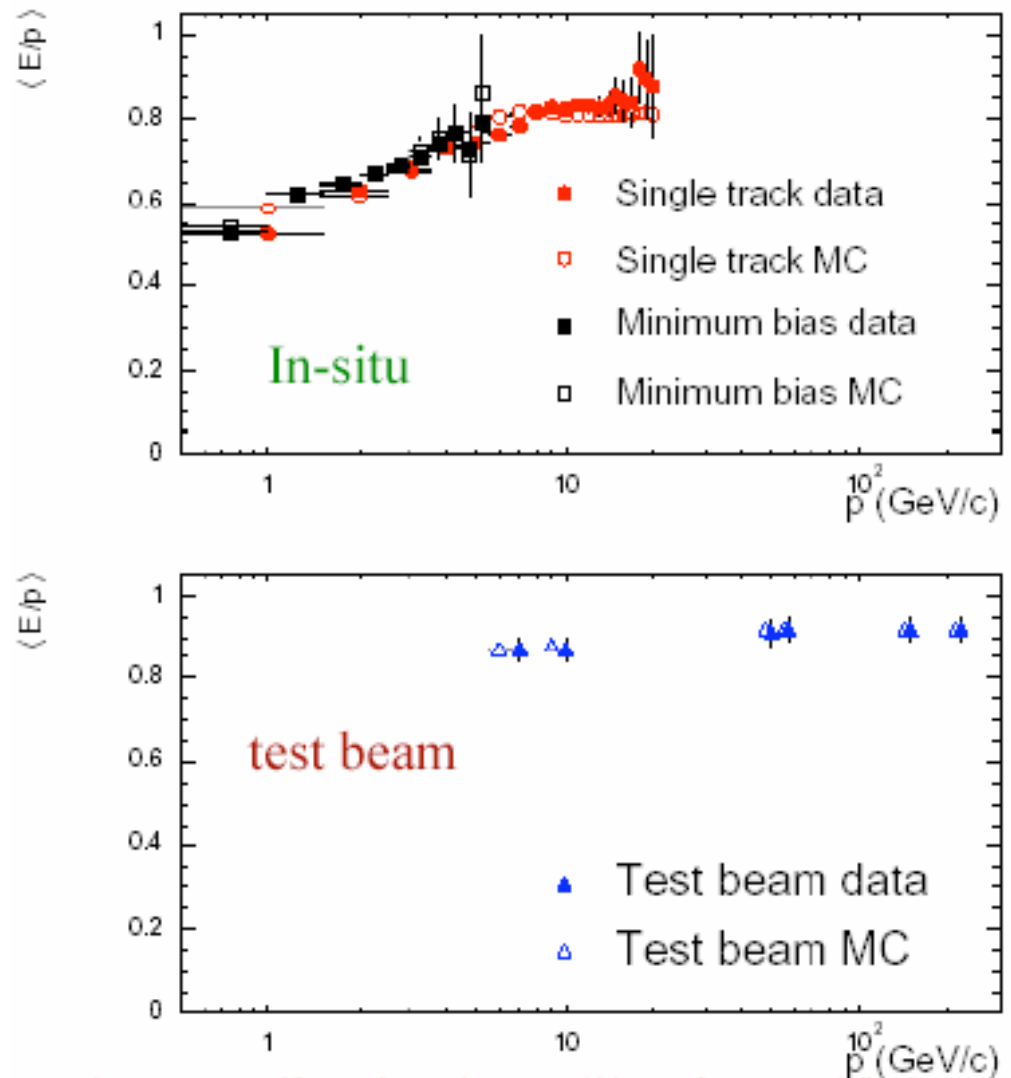
Testing Jets in Photon-Jet and Z-Jet Data

$$p_T{}^{jet}/p_T{}^{\gamma}-1$$

$$p_T{}^{jet}/p_T{}^{Z}-1$$
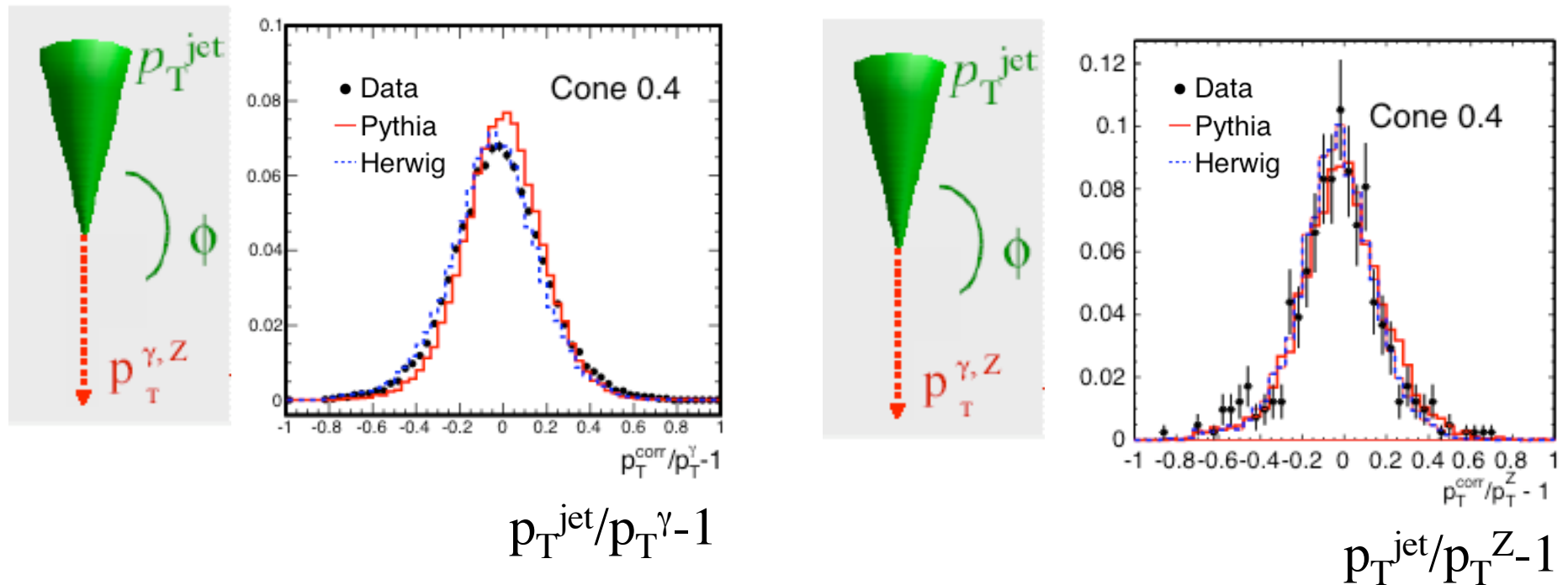
- Agreement within 3% but differences in distributions!
  - Data, Pythia and Herwig all a little different in photon-jet data
- These are physics effects!
  - Detailed understanding with higher statistics and newer MC in progress

Jet Energy Scale Uncertainties

About 3% of m_{top} when convoluted with ttbar p_T spectrum
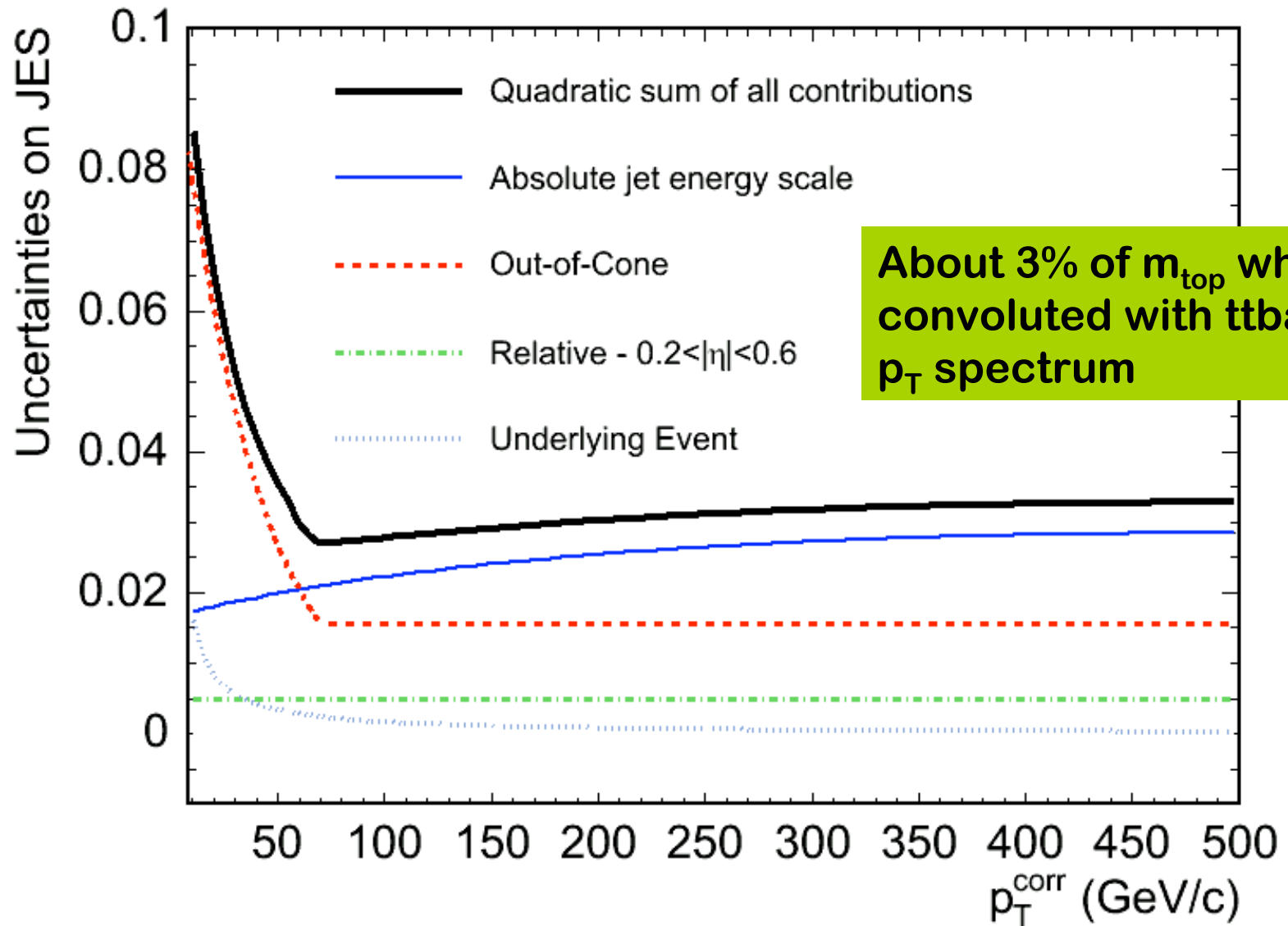
In-situ Measurement of JES

- Additionally, use W→jj mass resonance (M_{jj}) to measure the jet energy scale (JES) uncertainty
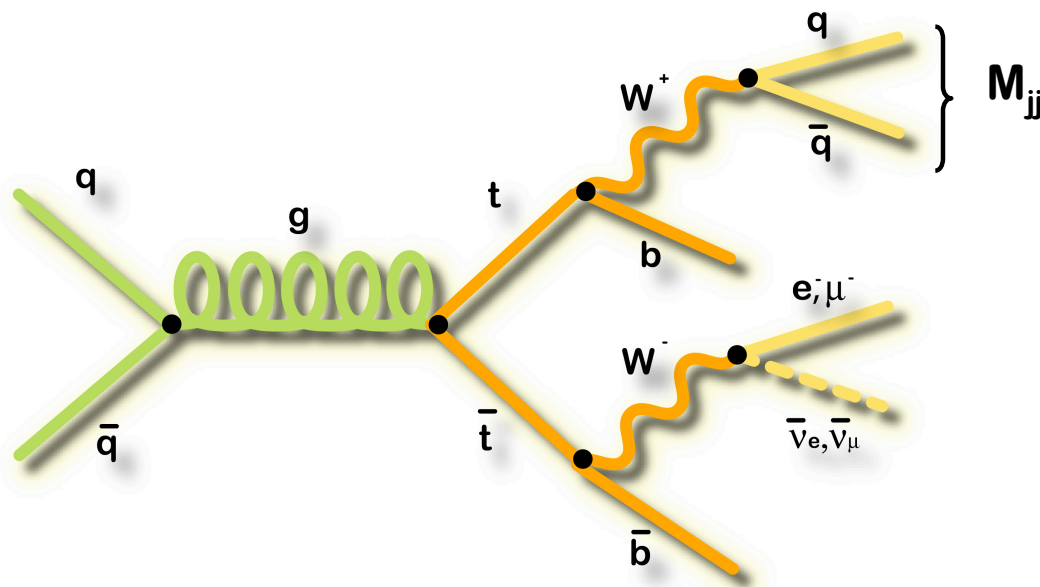
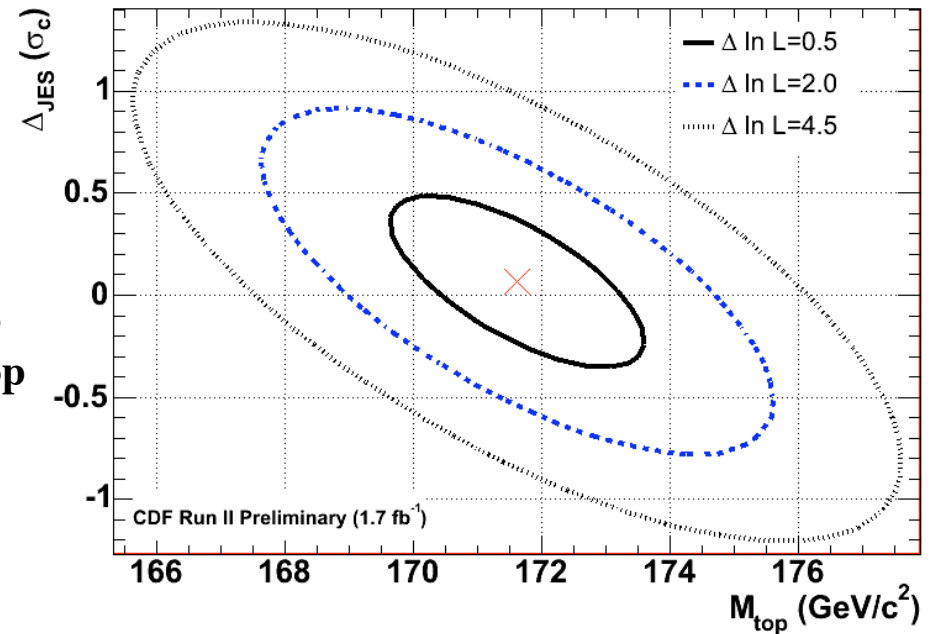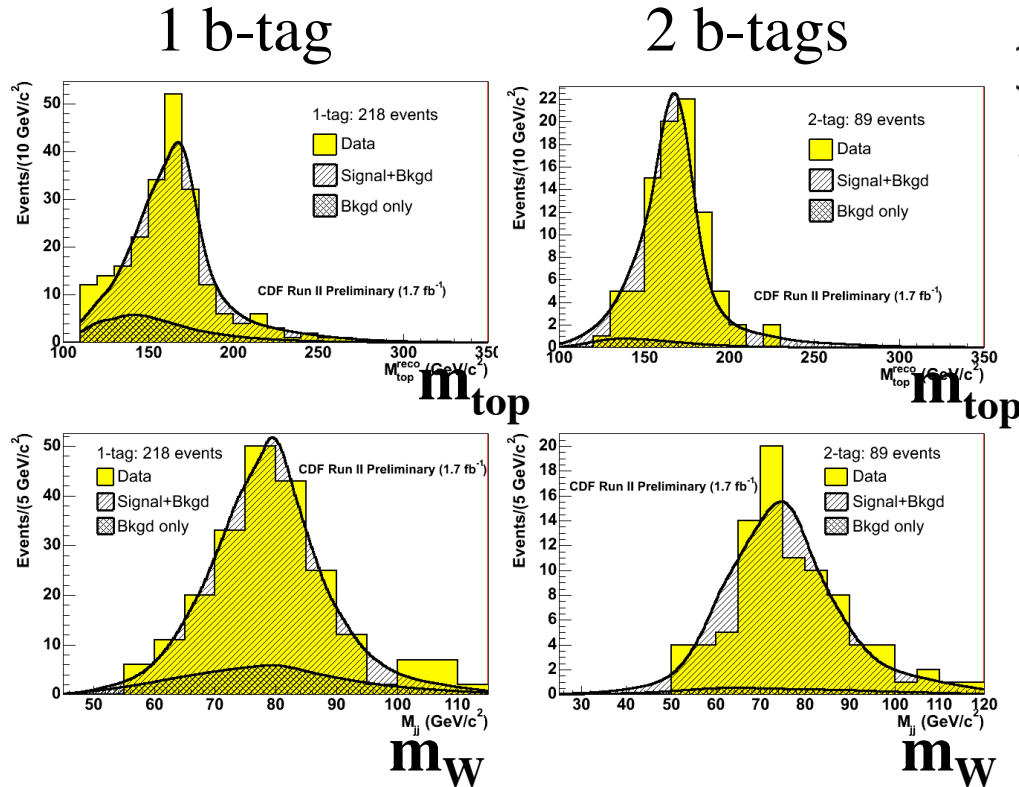**2D fit of the invariant mass of the non-b-jets and the top mass:**

JES $\propto$ M(jj)- 80.4 GeV/c^2

Measurement of JES scales directly with data statistics

Template Analysis Results on m_{top}

- Using 307 candidate events in 1.7 fb^{-1}
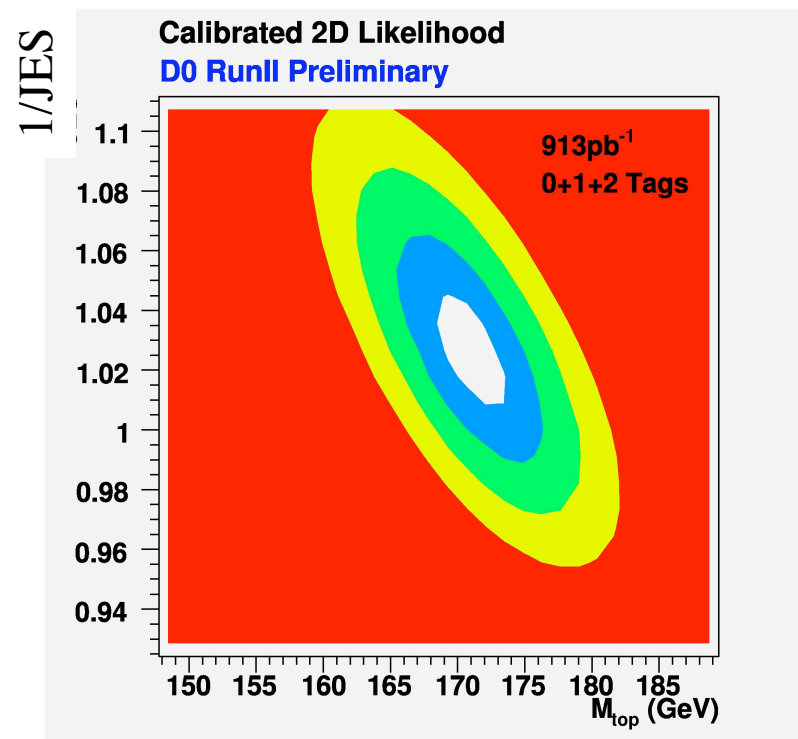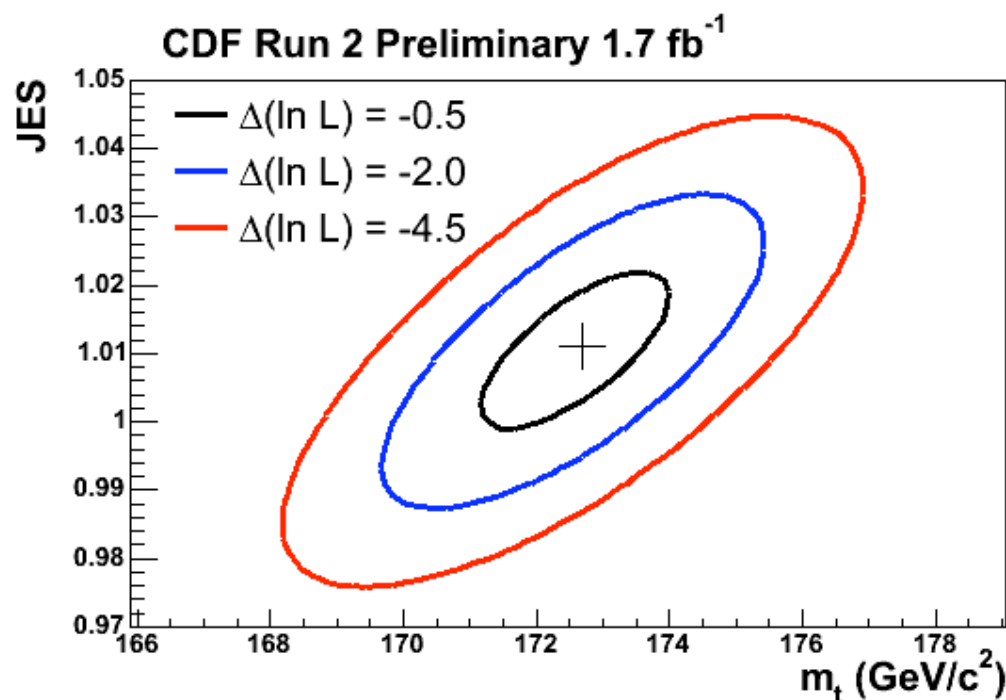- Using in-situ JES calibration results in factor two improvement on JES

1 b-tag

2 b-tags

$$m_{top} = 171.6 \pm 2.1 \pm 1.1 = 171.6 \pm 2.4 \text{ GeV/c}^2$$

Matrix Element Results on m_{top}

- Using most recent analysis of 343 candidates in 1.7 fb^{-1} m_{top} is:
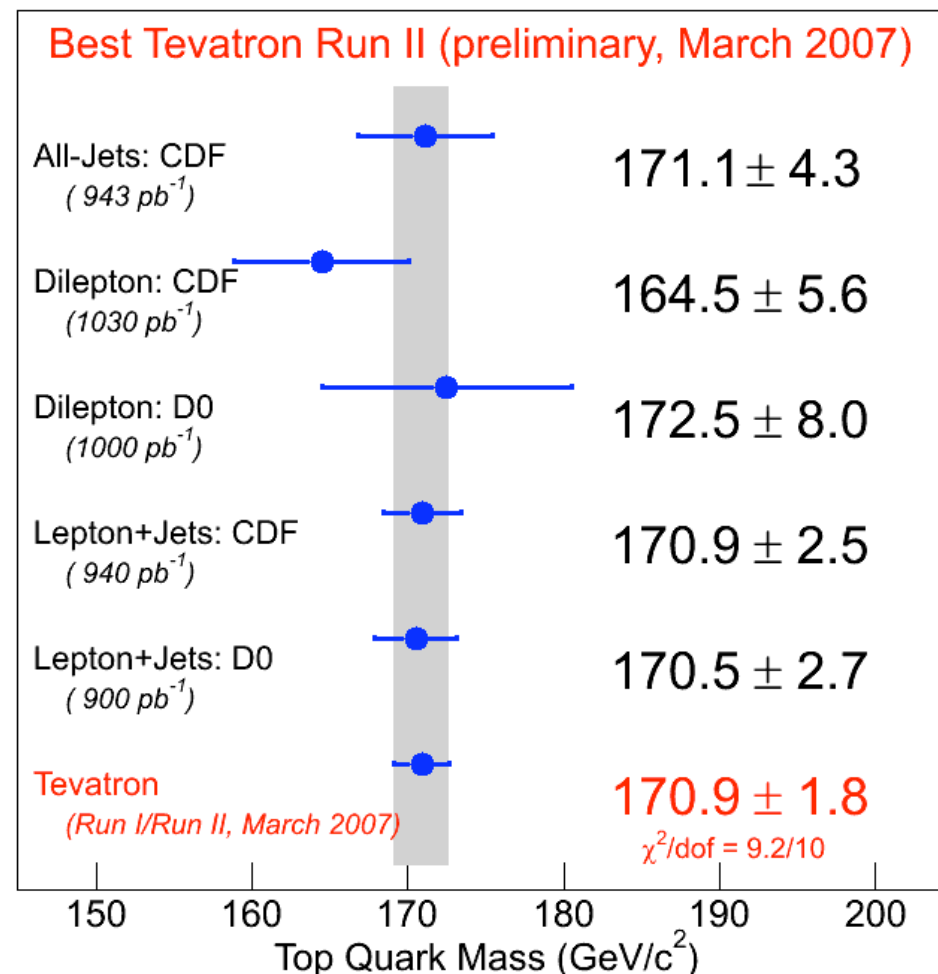
$$m_t = 172.7 \pm 1.3 \text{ (stat.)} \pm 1.2 \text{ (JES)} \pm 1.2 \text{ (syst)} \text{ GeV/c}^2 = 172.7 \pm 2.1 \text{ (total)} \text{ GeV/c}^2$$

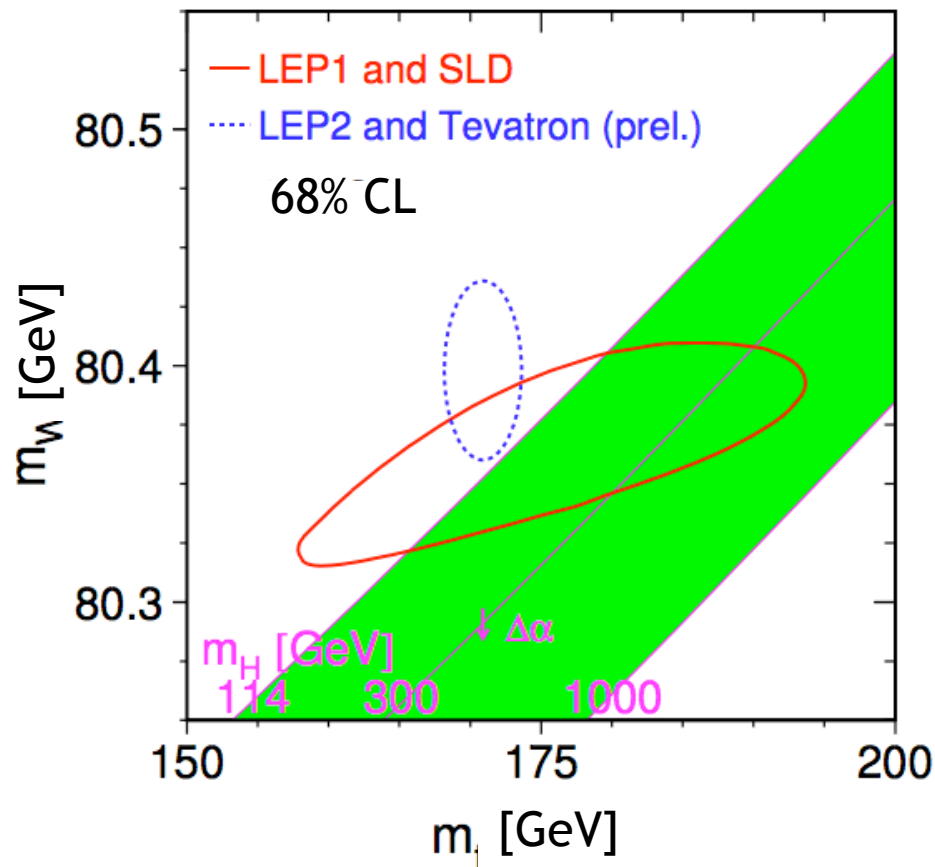**Consistent result. Slightly better precision than Template Method**

Combining M$_{top}$ Results

- **Excellent results in each channel**
  - Dilepton
  - Lepton+jets
  - All-hadronic

- **Combine them to improve precision**
  - Include Run-I results
  - Account for correlations

- **New uncertainty: 1.8 GeV**
 - Dominated by systematic uncertainties

Best Tevatron Run II (preliminary, March 2007)

	Top Quark Mass (GeV/c^2)
All-Jets: CDF (943 pb^{-1})	171.1 ± 4.3
Dilepton: CDF (1030 pb^{-1})	164.5 ± 5.6
Dilepton: D0 (1000 pb^{-1})	172.5 ± 8.0
Lepton+Jets: CDF (940 pb^{-1})	170.9 ± 2.5
Lepton+Jets: D0 (900 pb^{-1})	170.5 ± 2.7
Tevatron (Run I/Run II, March 2007)	170.9 ± 1.8 $\chi^2/dof = 9.2/10$

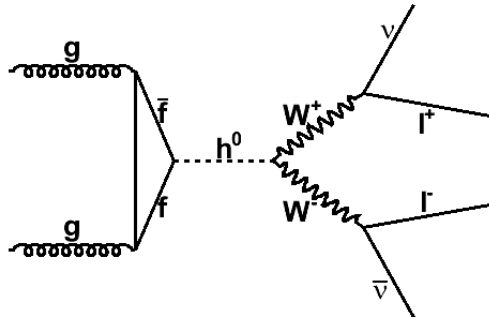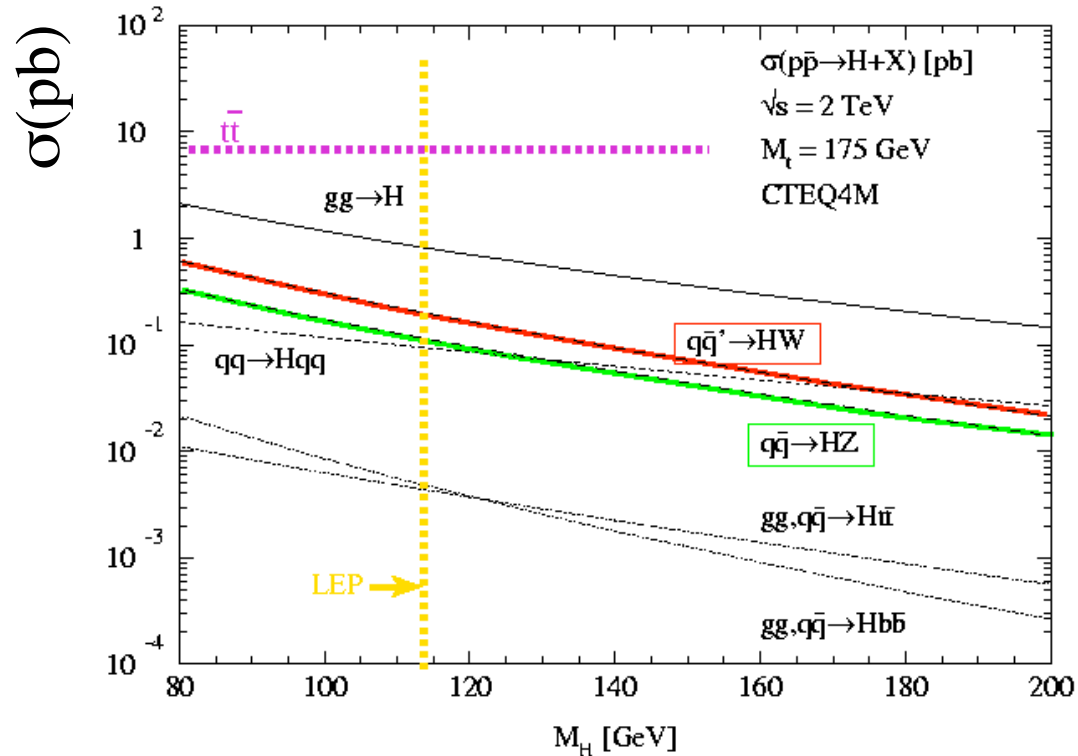# Implications for Higgs Boson

m_H constrained in the Standard Model

Direct searches at LEP2:
m_H>114.4 GeV @95%CL
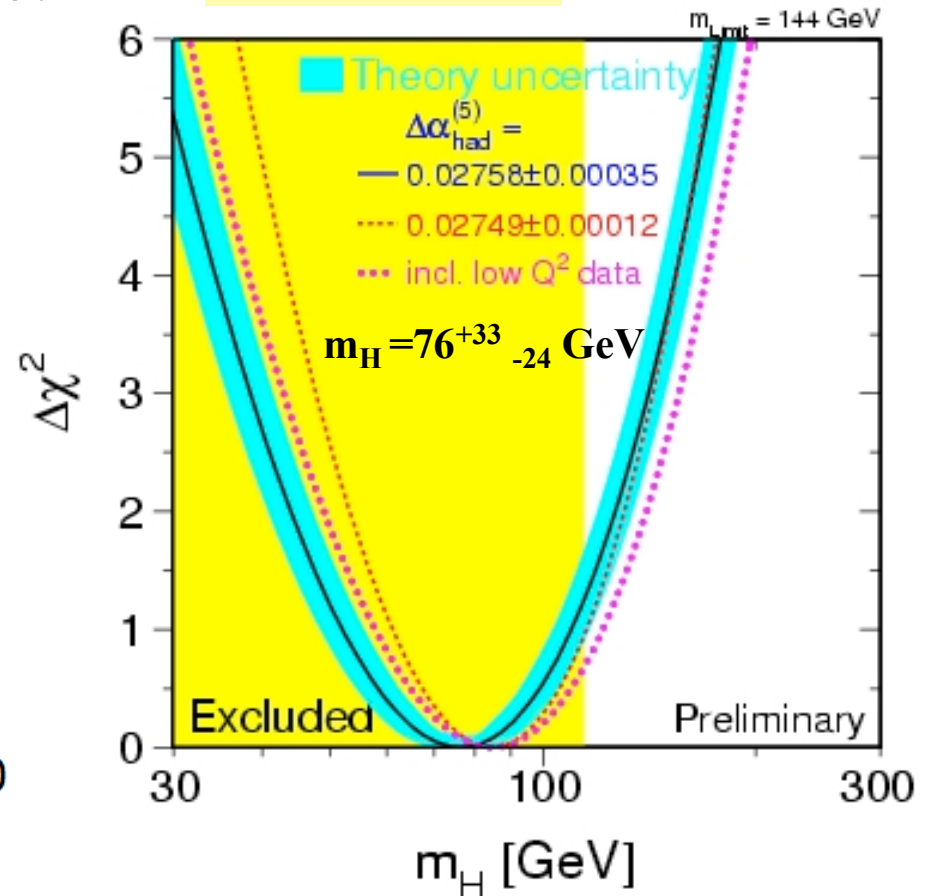
Indirect constraints:
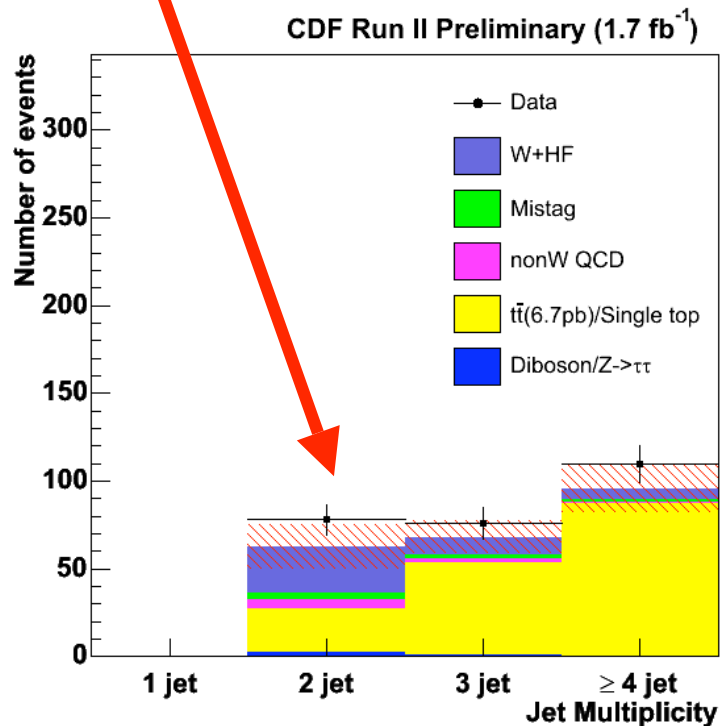m_H<144 GeV @95%CL

Higgs Production at the Tevatron
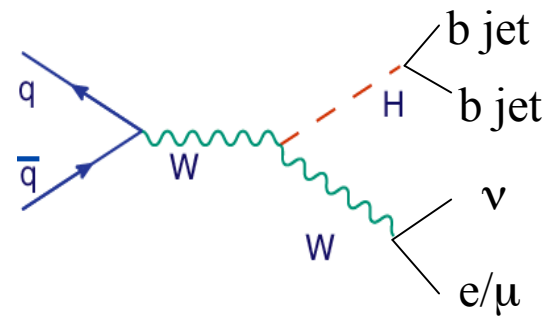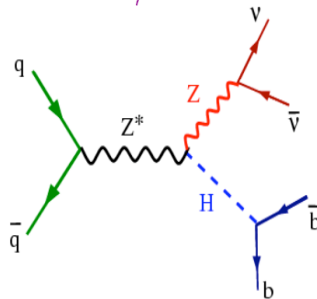
dominant: gg→ H, subdominant: HW, HZ

WH→lνbb

q

q̄

W , Z

H

W , Z

b jet

b jet

ν

e/μ

Now looking for 2 jets

CDF Run II Preliminary (1.7 fb^{-1})

Number of events

- Data
- W+HF
- Mistag
- nonW QCD
- $t\bar{t}$(6.7pb)/Single top
- Diboson/Z->ττ

1 jet   2 jet   3 jet   ≥ 4 jet
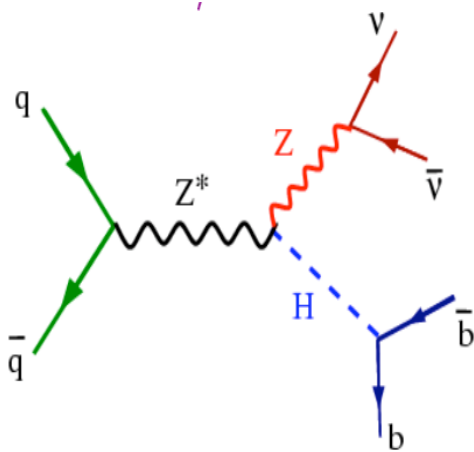**Jet Multiplicity**
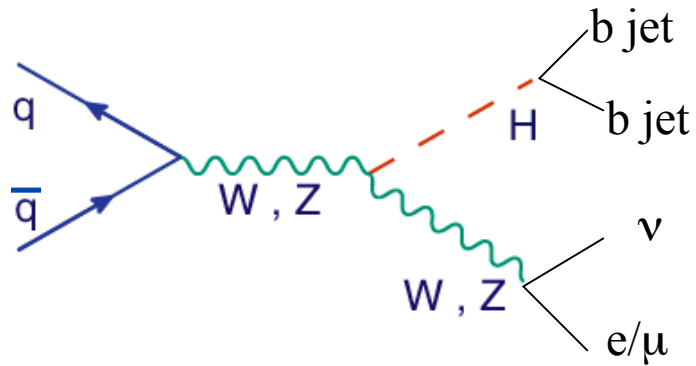
- **WH selection:**
  - **1 or 2 tagged b-jets**
  - **electron or muon with p_T > 20 GeV**
  - **E_T^{miss} > 20 GeV**

Expected Numbers of Events:
WH signal: 0.85   + 0.65
Background: 62±13 + 69±12

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ZH→ννbb


- **Event selection:**
  - ≥ 1 tagged b-jets
  - Two jets
  - $E_T^{miss} > 70$ GeV
  - Lepton veto
  - Veto missing E_T along jet directions

- **Big challenge:**
  - Background from mismeasurement of missing E_T
  - QCD dijet background is HUGE
    - Generate MC and compare to data in *control regions*
    - Estimate from data

- **Control:**
  - Missing E_T direction
  - Missing E_T in hard jets vs overall missing E_T

mismeasured   genuine
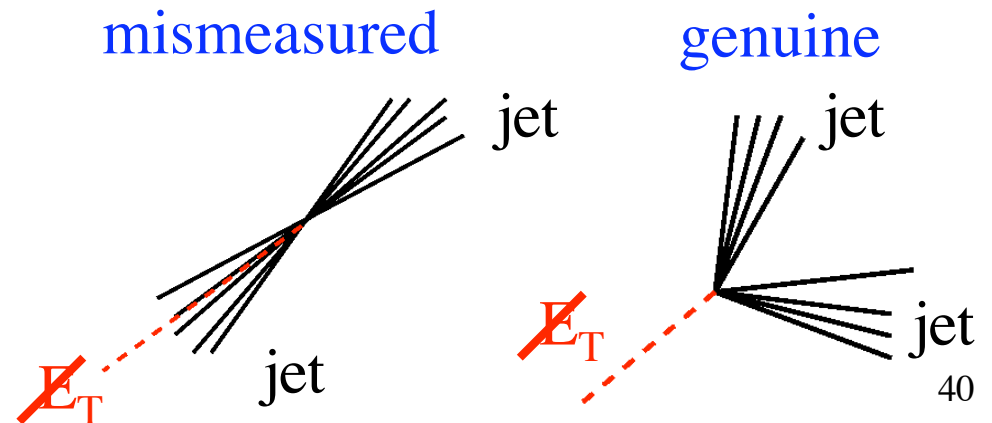
QCD Jet Background to ZH→ννbb

- **DØ uses data**

  - Define variable that can be used to normalize background

  - Asymmetry between
    - missing E_T inside jets and
    - overall missing E_T

  - Sensitive to missing E_T outside jets
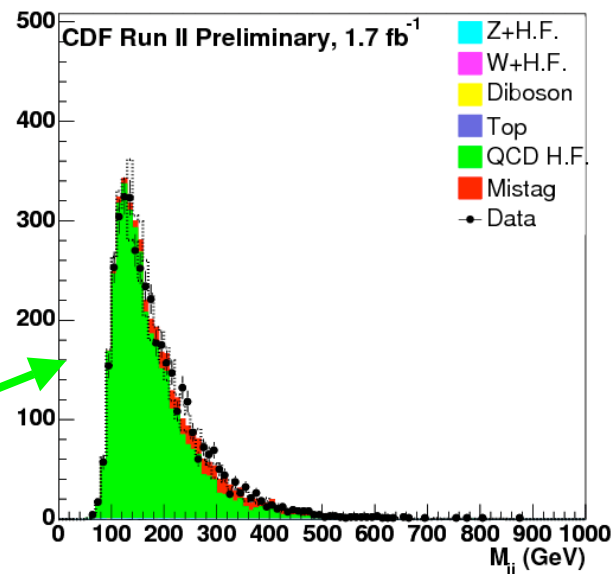   - Background has large asymmetry
    - Signal peaks at 0
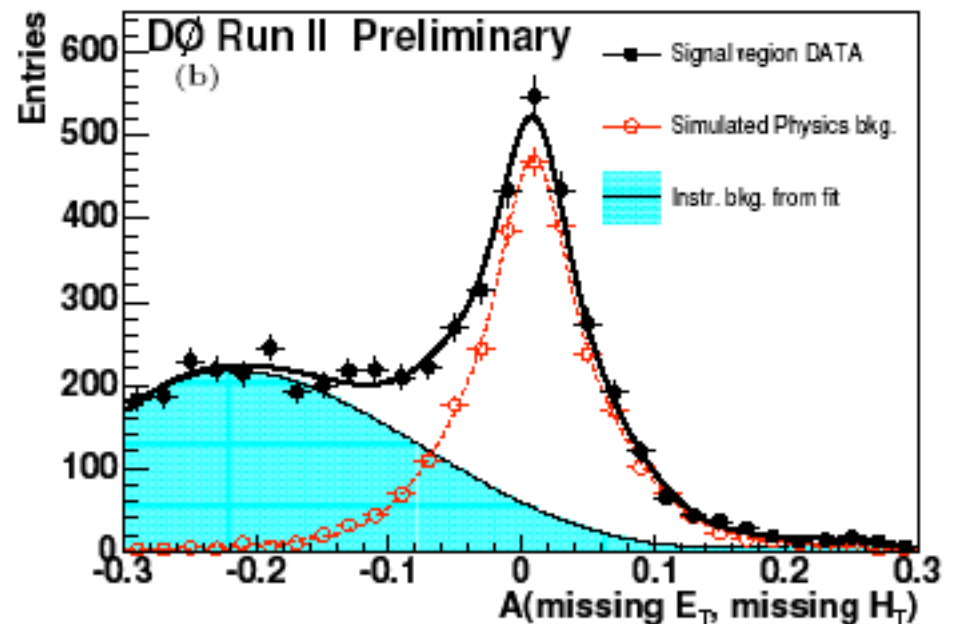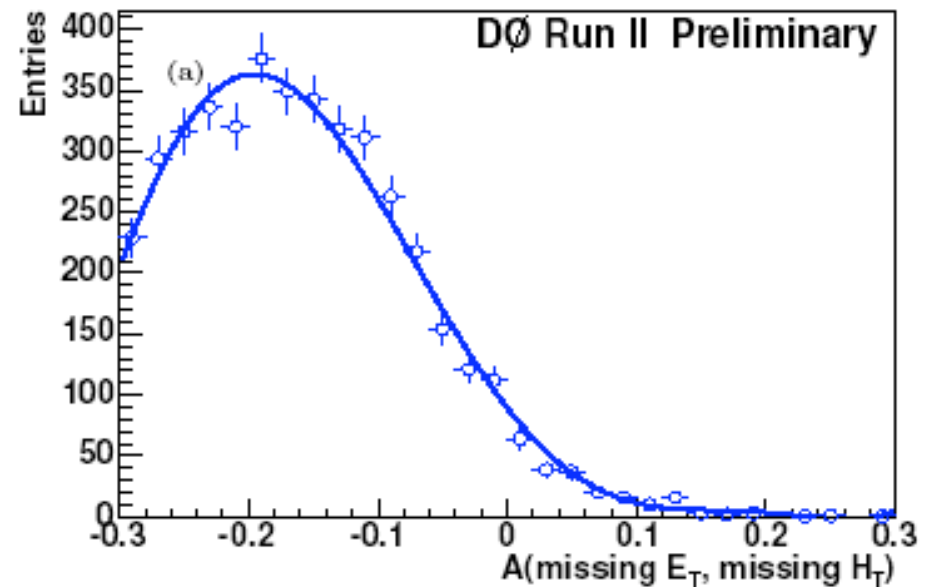
Background understanding using MC

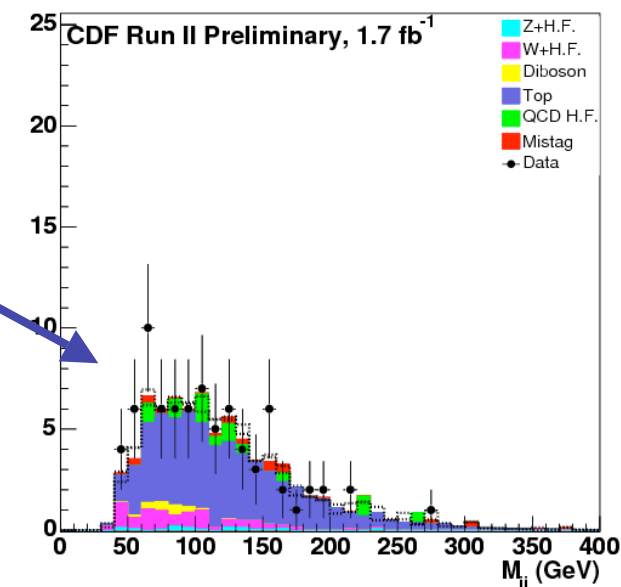- CDF use MC and check it in detail against data

"QCD" control region:
Jet aligned with missing E_T
$\Rightarrow$ Completely dominated by QCD jets and mistags

"EWK" control region:
Identified lepton in event
=> Dominated by top

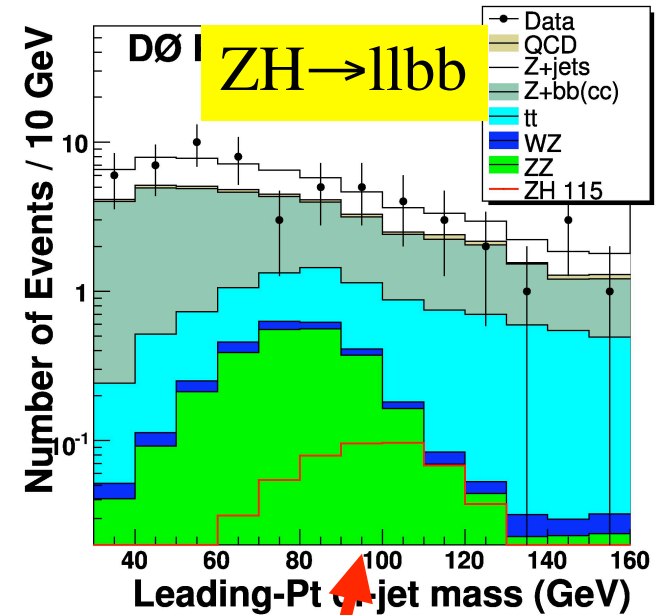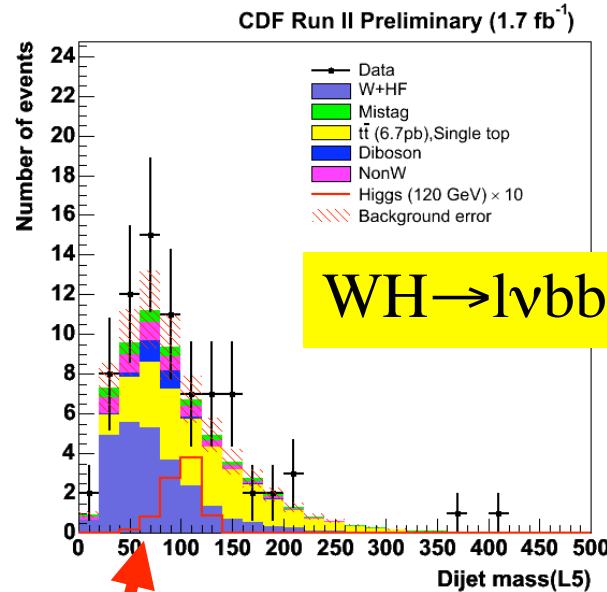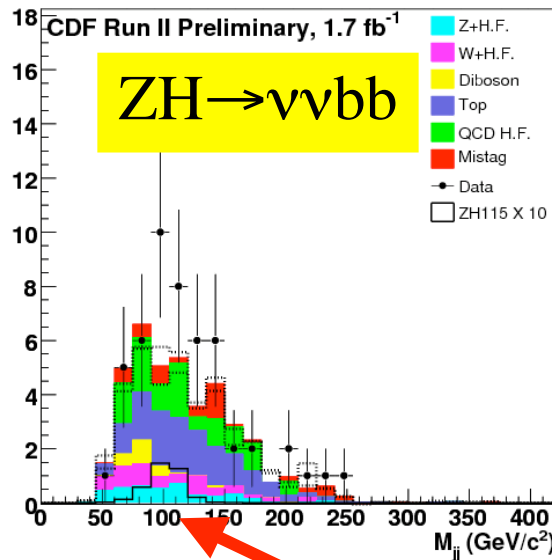Look at data only when control regions look satisfactory

Dijet Mass, CR1, L+L
CDF Run II Preliminary, 1.7 fb^{-1}
Z+H.F.
W+H.F.
Diboson
Top
QCD H.F.
Mistag
Data
M_{jj} (GeV)

Dijet Mass, CR2, L+L
CDF Run II Preliminary, 1.7 fb^{-1}
Z+H.F.
W+H.F.
Diboson
Top
QCD H.F.
Mistag
Data
M_{jj} (GeV)

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Dijet Mass distributions


- **Backgrounds still much larger than the signal:**
  - Further experimental improvements and luminosity required
  - E.g. b-tagging efficiency (40->60%), *NN selection*, higher lepton acceptance

Single Top Quark Production

- Interesting benchmark for Higgs production
  - Same final state as WH
    - cross section 10 times higher though!
  - S/B too low for counting experiment
    - Advanced techniques are employed:
      - Boosted decision trees (DØ)
      - Neural Networks (CDF/DØ)
      - Matrix Element (CDF/DØ)
      - Likelihood (CDF)

S= 61+/-11
B=1042+/-218
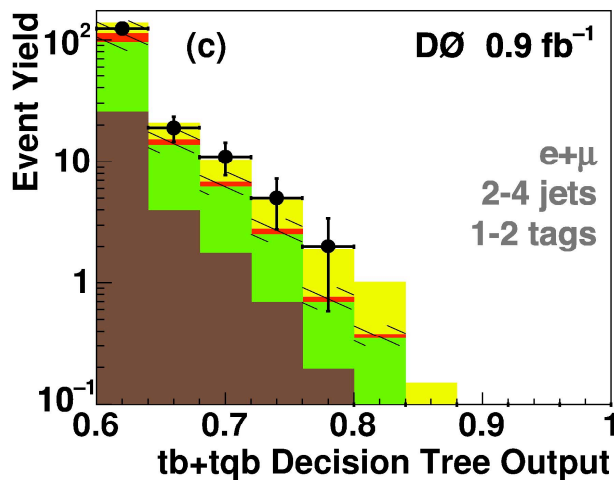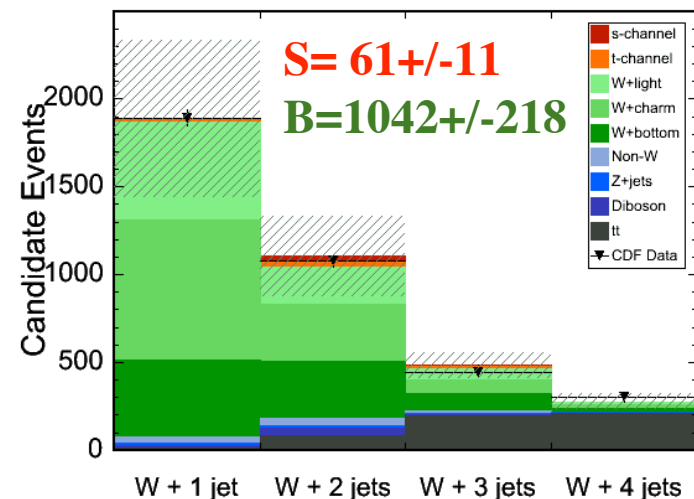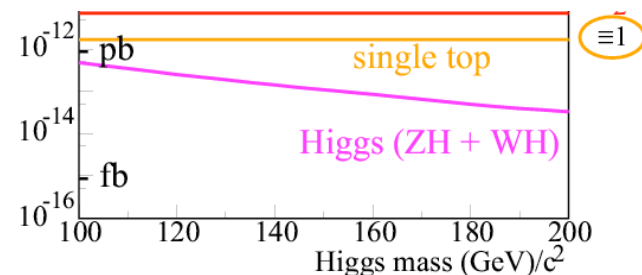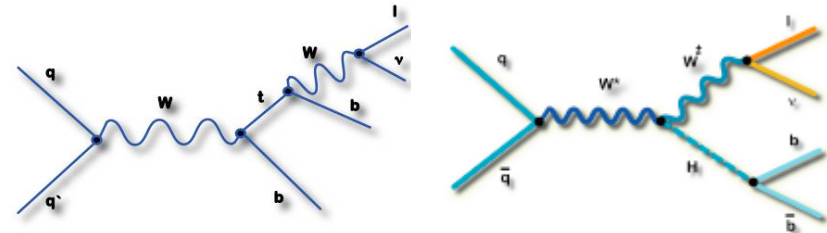
- 12/06: DØ see 3.4σ with 0.9 fb^{-1}: σ=4.9+/-1.4 pb
- 07/07: CDF see 3.1σ with 1.5 fb^{-1}: σ=3.0$^{+1.2}_{-1.1}$ pb
- Both Agree with SM: σ=2.9+/-0.4 pb

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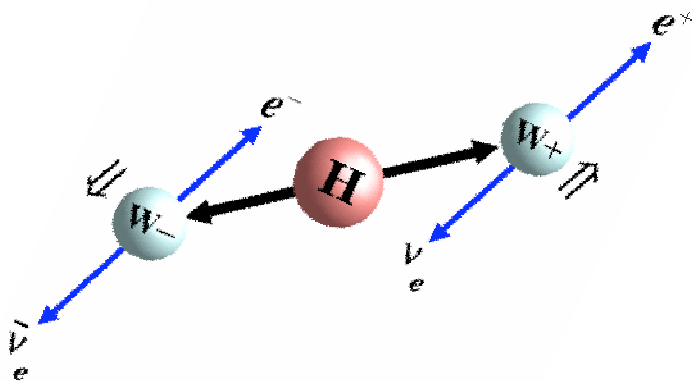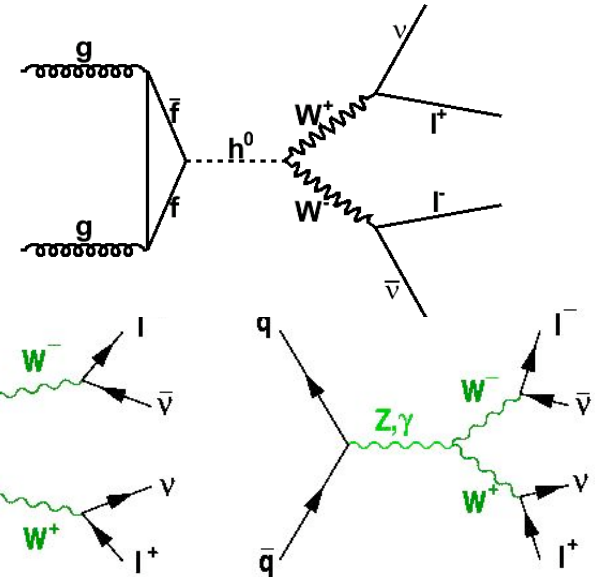# Higgs Search with Neural Network
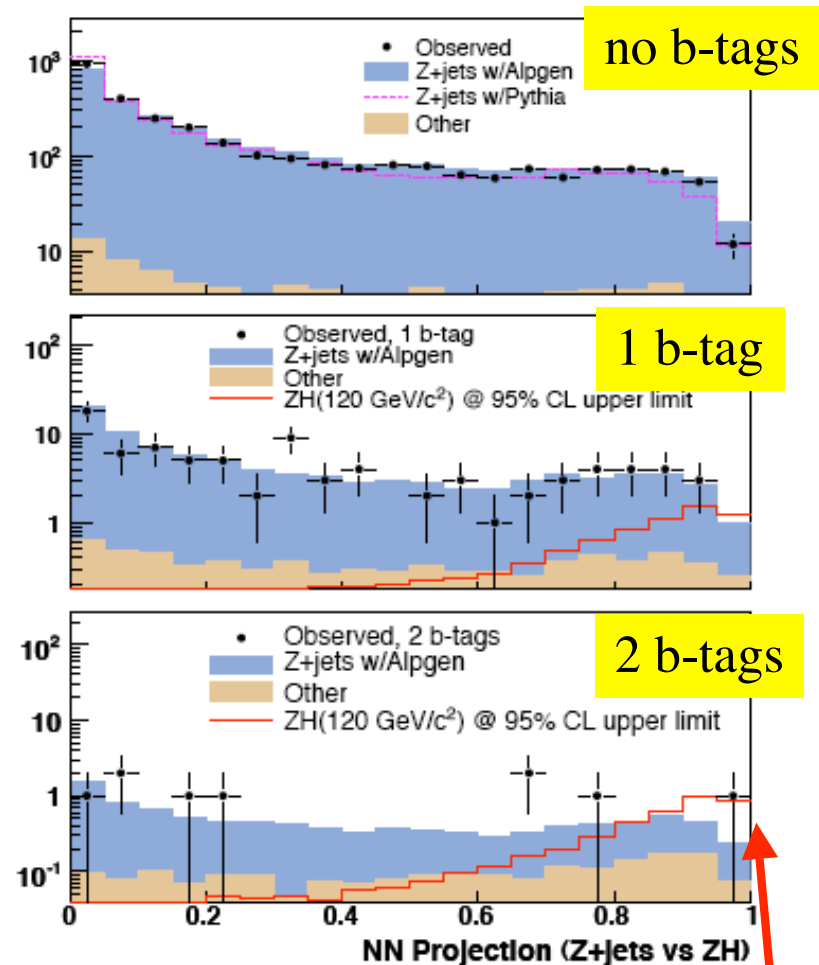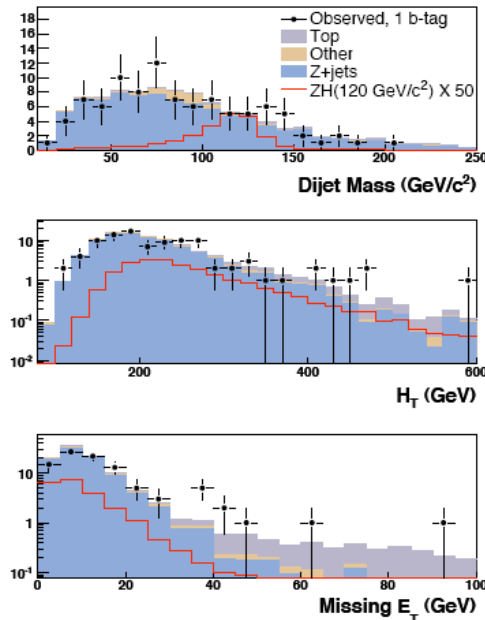
- Construct neural network can be powerful to improve discrimination:
  - Here 10 variables are used in 2D Neural Network

- Critical:
  - understanding of distribution in control samples

$$\sigma_{SM}(ZH) \times 19$$

H → WW$^{(*)}$ → l$^+$l$^-$ν$\bar{ν}$

- Higgs mass reconstruction impossible due to two neutrinos in final state
- Make use of spin correlations to suppress WW background:
  - Higgs has spin=0
  - leptons in H → WW$^{(*)}$ → l$^+$l$^-$νν are collinear
- Main background: WW production

10x 160 GeV Higgs

CDF Run II Preliminary $\int$ L dt = 1.9 fb^{-1}

Events / 0.1 rad

Δφ leptons

H→WW$^{(*)}$→l$^+$l$^-$νν (l=e,μ)
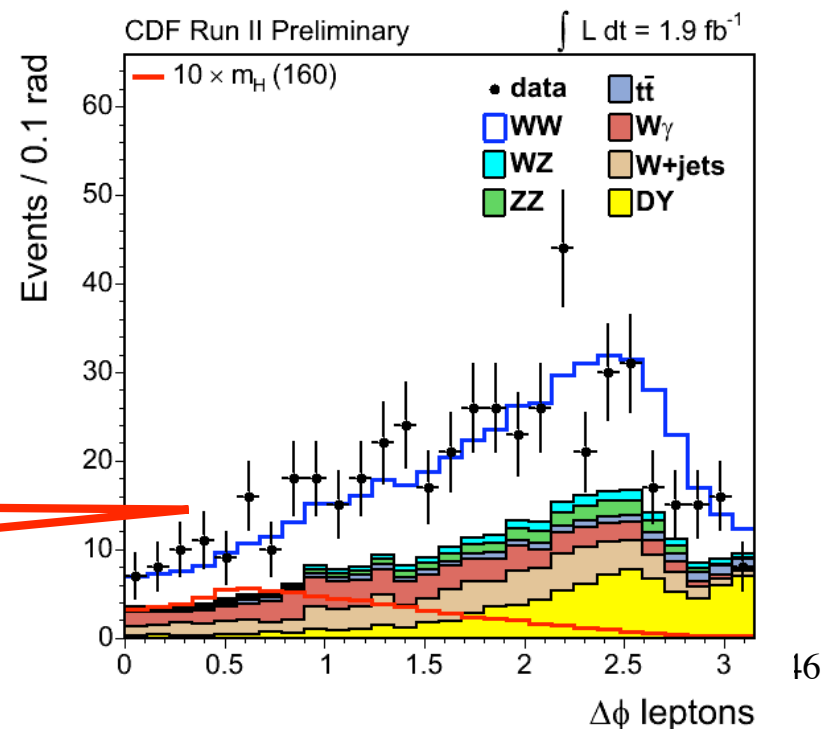
- **Event selection:**
  - 2 isolated e/μ :
    - p_T > 15, 10 GeV
  - Missing E_T >20 GeV
  - Veto on
    - Z resonance
    - Energetic jets

- **Separate signal from background**
  - Use matrix-element or Neural Network discriminant to

- **Main backgrounds**
  - SM WW production
  - Top
  - Drell-Yan
  - Fake leptons

Ratio to Standard Model

Tevatron Run II Preliminary
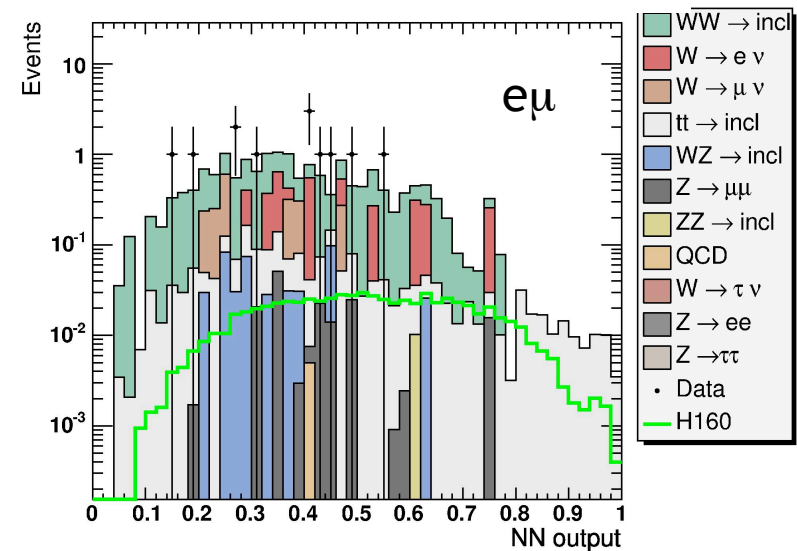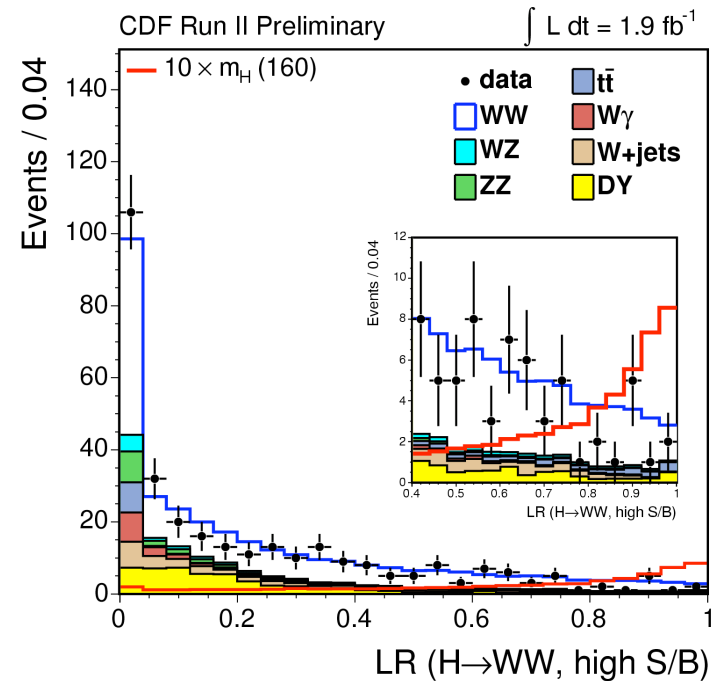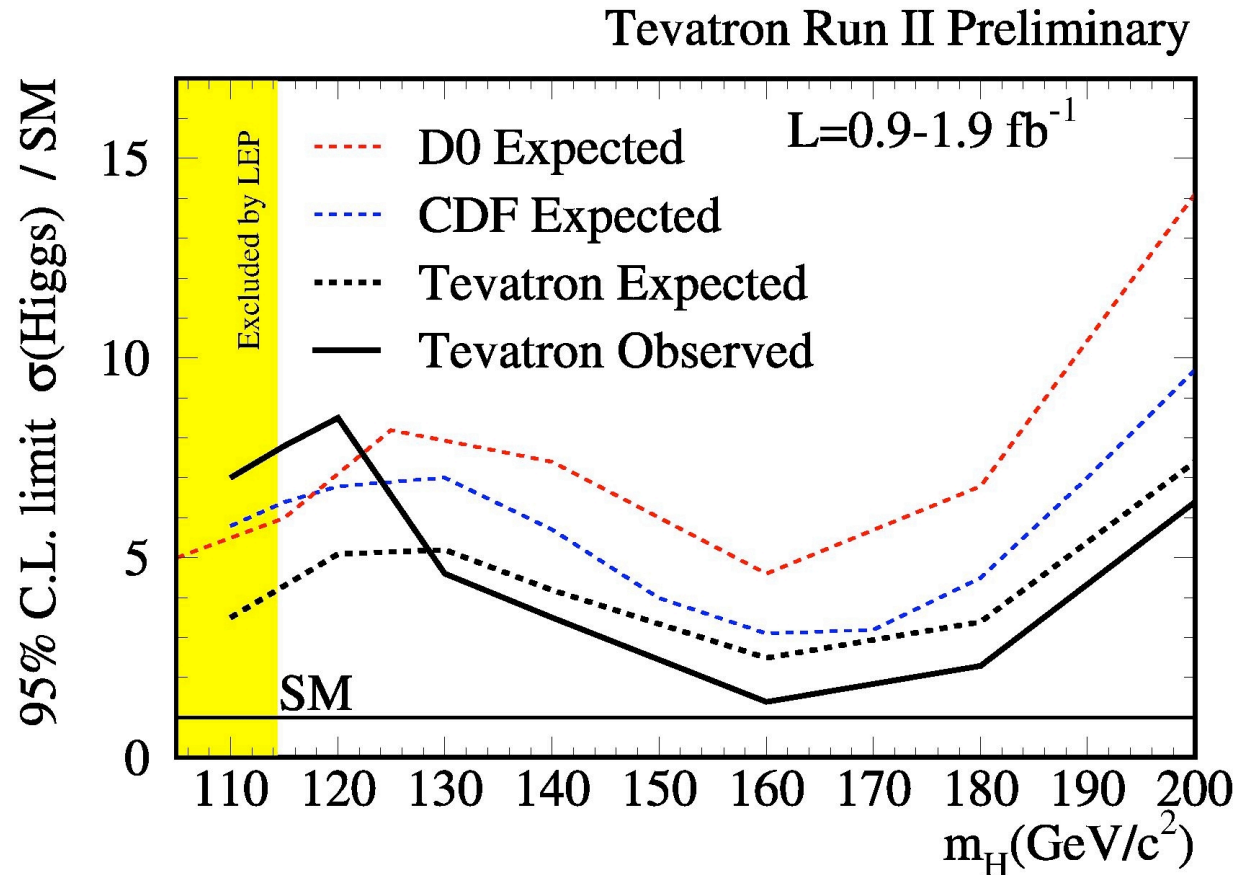
- Further experimental improvements and luminosity expected
  - Will help to close the gap
  - Expect to exclude 160 GeV Higgs boson soon
  - At low mass still rather far away from probing SM cross section

Conclusions
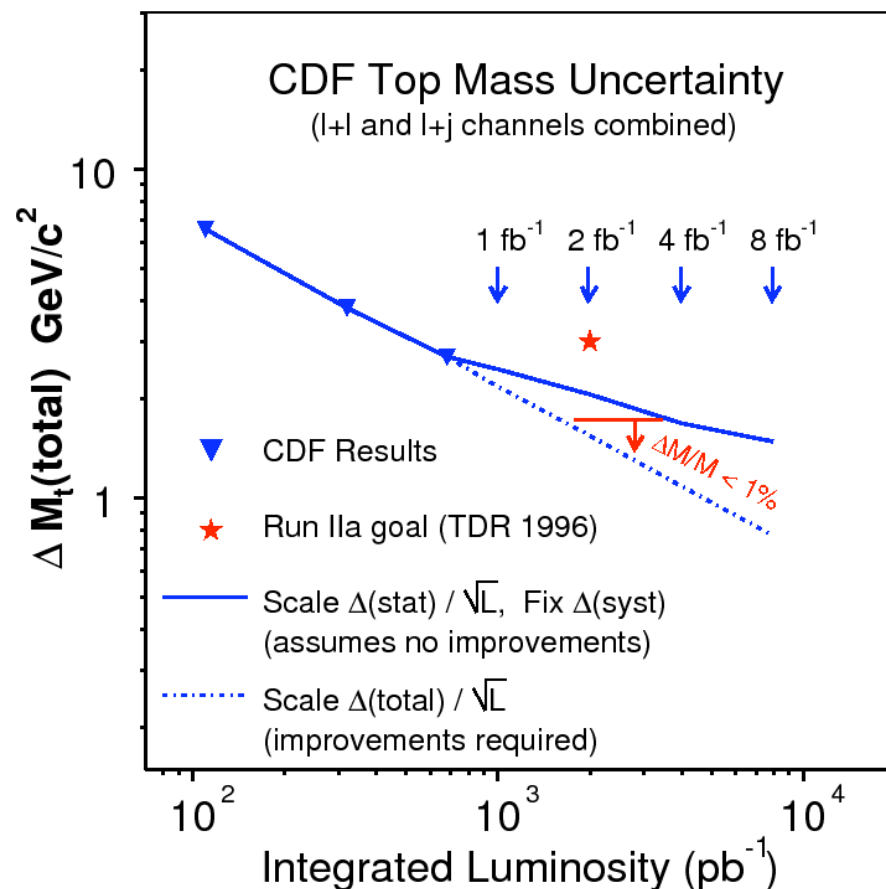
- The W boson, top quark and Higgs boson require
  - Lepton momentum scale
  - b-tagging
  - Jet energy calibration

- Probe electroweak sector of the Standard Model
  - $\delta M_W/M_W = 0.07\%$, $\delta M_{top}/M_{top} = 1\%$
  - $m_H < 144$ GeV at 95% CL

- Higgs searches ongoing
  - Steady progress towards probing SM cross section
    - Expectations were set high and collaborations are working on meeting these specs
  - Expect sensitivity to 160 GeV Higgs with $\int L = 2\text{-}4 \text{ fb}^{-1}$

Backup

Systematic Uncertainties

Source	δm_{top} (GeV/c^2)
Remaining JES	1.0
Initial State QCD radiation	0.3
Final State QCD radiation	0.2
Parton distribution functions	0.3
MC modelling	0.2
background	0.6
B-tag	0.2
MC model	0.2
total	1.16

CDF Top Mass Uncertainty
(l+l and l+j channels combined)

▼ CDF Results

★ Run IIa goal (TDR 1996)

Scale Δ(stat) / √L, Fix Δ(syst) (assumes no improvements)

Scale Δ(total) / √L (improvements required)

ZH→ννbb candidate